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PERFORMANCE EVALUATION OF INTEGRATED METOC MEASUREMENT SYSTEM SUPPORTING NAVAL OPERATIONS

by

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ABSTRACT

MORIAH is a shipboard METOC measurement system planned for installation on 72 AEGIS ships. A prototype MORIAH system (SEAWASP) was deployed for an 8 month period on two CG's: USS Anzio and USS Cape St. George. The SEAWASP accuracy and reliability were evaluated in the context of the MORIAH Operational Requirements Document (ORD) and AEGIS operating requirements. Measures of accuracy were RMS differences between simultaneous ship measurements when their separation was less than 10 and 5 kilometers. Measures of reliability were based on the number of mast average records possible in a period, recorded in a period, and validated in a period. For ORD accuracy, only air temperature and relative humidity met ORD Threshold requirements. For ORD reliability, Anzio's system did not meet requirements because a power surge caused failure of several ship systems including SEAWASP. Applying AEGIS accuracy requirements, only relative humidity passed. This result caused ship evaporation duct heights to agree during unstable and neutral conditions but significantly diverge in low wind / humidity and stable conditions. SEAWASP did not provide sufficient reliability for continuous propagation assessments. Validated data for both ships were less than 50%. Significant gains (25%) in reliability performance were shown using modified selection criteria.

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I. INTRODUCTION

Modern battlespace challenges and advanced naval system capabilities have increased the importance of accurate and timely depictions of environmental conditions. The SECNAV, CNO, and CMC (1999) Department of the Navy Posture Statement states that forward presence, deterrence, sea / area control, and power projection are the enduring concepts of Naval forces to implement National Military Strategy. In view of current crises and conflicts, the process of executing these concepts have changed the nature of the battlespace environment. The conditions have become more complex and dynamic as it has shifted from the wide-area open ocean to the localized littoral environment where naval forces must operate in close proximity to hostile forces ashore. The AEGIS Weapon System is the premiere air defense weapon system in the U.S. Navy, but operational tools to optimize AEGIS system parameters to take advantage of atmospheric conditions do not currently exist. Current operational Meteorology and Oceanography (METOC) products do not have the spatial or temporal resolution needed to capture the real-time littoral environment conditions that affect the performance of the AEGIS Weapon System.

In the area denial problem of littoral operations, the cruise missile has become the principal threat against surface ships and a challenge to the AEGIS Weapon System. Their small radar cross-section, low cruising altitude, and high speed provide a limited window of opportunity for detection and successful engagement. While technology has improved sensor effectiveness and expanded radar mission capabilities, the resulting sensor performance is increasingly dependent on an accurate and timely assessment of the operational environment.

There are two requirements for accurate assessment of the environment's impact on weapon system performance. The first is the implementation of efficient and accurate sensor performance models. The second is the high resolution and 4-dimensional (space and time) descriptions of the influencing METOC parameters. For electromagnetic (EM) waves, advanced propagation models solve the parabolic wave equation (PE) with a numerical technique such as the Fourier split-step. They have proven to be in excellent agreement with measured propagation loss (Ganz and Ryan, 1997). PE based EM models are highly dependent on the accuracy and resolution of environmental initialization. For shipboard sensors to

accurately characterize the ambient environment, contamination of the measurements by ship influences must be minimized.

This thesis is an evaluation of the accuracy and reliability of the performance of a deck-level continuous METOC measurement system planned for installation on 72 AEGIS cruisers and destroyers. The METOC system is a part of the Johns Hopkins University / Applied Physics Laboratory (JHU/APL) developed Shipboard Environmental Assessment / WeApon System Performance system (SEAWASP), (Konstanzer et al. 1997). SEAWASP was developed as a tactical decision aid for the AEGIS Program Office (PMS-400). The measurement component has been deployed on several Ticonderoga class cruisers including the USS Anzio (CG 68) and USS Cape St. George (CG 71).

SEAWASP is the environmental characterization (EC) and radar propagation assessment (RPA) sub-system for a program under development that is scheduled to start procurement in CY00. The program and overall system is called MORIAH. A primary function of SEAWASP is support for the AEGIS Weapon System with real-time radar performance assessments based on continuous METOC measurements. In order to evaluate SEAWASP instrument / system performance, this thesis uses system specifications listed in the MORIAH Operational Requirements Document (ORD) and AEGIS requirements provided by the AEGIS Program Office (PMS-400).

The history and context of METOC measurement requirements and MORIAH specifications are provided in the Chapter II. General refractivity theory and model applications necessary to relate the results and conclusions are discussed in the Chapter III. An overview of the system hardware and software components is presented in Chapter IV. An introduction to the operational significance of this system's capability is provided in Chapter V. The data set and processing steps are described in Chapter VI. The basis for the performance evaluation is discussed in Chapter VII followed by the results in Chapter VIII. Chapter IX addresses these results relative to the ORD and AEGIS requirements. Chapter X, the final part of the thesis, provides recommendations based on this performance evaluation.

II. BACKGROUND

Shipboard METOC measurements are a standard part of ship operations, and the environment plays a key role in operations relating to navigation, weapon systems, and aircraft. The increased sensitivity of advanced sensors systems to METOC conditions has been the catalyst for the SEAWASP system development. An operational evaluation of SEAWASP is necessary even though METOC measurements have been made on operational ships for years. SEAWASP is the first continuous and automated system to be integrated with the AEGIS Weapon System. The primary goal of this integration has been to optimize the AN/SPY-1 radar configuration using real-time assessments of the atmospheric influence on radar propagation. Such optimization has not occurred before except on a few demonstration ships in a testing environment. In this section we consider the need for a continuous and automated METOC measurement system.

A. ENVIRONMENTAL ISSUES IN RADAR OPERATIONS AT SEA

The need for an environmental component in the radar configuration system has been demonstrated through AEGIS live-fire missile exercises. In the course of ship training and readiness exercises, AEGIS platforms must successfully engage sea-skimming supersonic missiles. In order to determine the theoretical target detection range versus actual ship performance for post-exercise analysis and evaluation, specially instrumented helicopters fly along the target flight path collecting refractivity data to calculate low elevation refractivity conditions before and after target launch. From the comparison of the measured refractivity and actual radar performance, the analysis can assess the magnitude of the environment's impact on the AEGIS Weapon System and evaluate current radar performance models. Three important results of these exercises highlight the environment's critical role in predicting radar performance and determining METOC support requirements for the AEGIS Weapon System.

The first result shows the importance of refractivity conditions. Analyses of the helicopter data and comparisons with observed radar performance have shown that refractivity conditions can

significantly modify system performance by changing the radar range and sea clutter return (Goldhirsh and Dockery, 1994). Surface ducts were found to be the primary cause of extended surface radar ranges which could greatly increase detection range and reaction time.

The second result demonstrated the importance of timeliness for practical radar performance assessments. To gather the environmental data for determining refractive conditions, leased helicopters were equipped with special instruments which recorded data along a saw tooth pattern along the missile's flight path. The analysis of refractivity was complex and not used for real-time feedback. The lack of real-time feedback prevented the use of environmental information to optimize radar configuration.

The third result demonstrates the importance of METOC support and performance assessment integration with ship weapon systems. The current operational tools to describe environmental refractivity conditions require METOC trained personnel to be deployed onboard AEGIS platforms for both measurement and analysis. The current METOC support is not integrated with ship systems so that METOC expertise is also needed to interpret results of the environmental analysis for the system operators. An example of consequences when real-time environmental support is unavailable is provided by the following description from a MISSILEX with two AEGIS ships (Dees, 1997).

> Without real time environmental assessments, each ship made an assumption about the environment. They were significantly different which led to different decisions about the required radar configuration to detect and engage the sea-skimming supersonic target. The two ship's radar sensitivity settings were not the same. The ship that chose the greater sensitivity was operating the radar with a large amount of clutter, and while the target was detected and successfully engaged, an additional missile was fired at a sea clutter track. The second ship never detected the target.

These issues motivated the AEGIS program office to develop an onboard integrated environmental system which continuously and automatically measures local conditions in operational environments to provide accurate real-time performance assessments for optimal system configuration. It was in this context that JHU/APL developed SEAWASP. The engineering objectives of SEAWASP are to assist a ship's radar controller in optimizing the configuration of the AN/SPY-1 radar based on real-time performance predictions and reduce the shortcomings of existing METOC support systems: reliability, accuracy, manpower requirements, personnel safety, and ship integration. SEAWASP is very different

from traditional METOC support since it is both automated and designed to continuously sample the environment for depicting near-surface refractivity.

Assessment of the atmosphere's affect on near-surface propagation requires descriptions of the refractivity gradients from the surface through the capping inversion up to 3,000 ft. These profiles must have higher resolution than normally required for conventional METOC support. Refractivity profile requirements for assessment of AEGIS air defense capability have been shown to be 10 ft (~ 3 m) below 500 ft and evaporation duct height estimates within a few ft (~ 2 m) by Dockery (1997). Operational requirements for future deployed profile measurement systems are specified to provide these values. Further, accurate and continuous measurement of sea-surface and deck-level atmospheric properties is required to describe both temporal and spatial variations that are significant to propagation conditions to a moving ship. For AEGIS air-defense capabilities, Dockery gives deck-level measurement and acquisition requirements as 5-minute averages with 0.5 Hz minimum sampling rate.

B. MEASUREMENT PROGRAMS SUPPORTING ELECTROGMAGNETIC (EM) OPERATIONS

MORIAH is a joint Chief of Naval Operations (N88, N86, N85, and N096) and Naval Air Systems Command (PMA 251) program which addresses the upgrade to existing METOC measurement systems and incorporation of SEAWASP capability in the future MORIAH system (CNO N096, 1998). As an overview, MORIAH represents the consolidation and combination of two existing programs: New Digital Wind Measuring and Indicating System (NDWMIS) and Shipboard Meteorological and Oceanographic Observing System Replacement (SMOOS(R)). An Operational Requirements Document (ORD) exists for this instrumentation suite and it reflects resources and requirements for all ships, ORD for MORIAH (1998). The ORD addresses SEAWASP through requirements of providing real-time, continuous METOC measurements on the ships for use in the evaporation duct / near-surface refractive profile model and input to the Navy adopted propagation model. A requirement exists to demonstrate that current or prototype METOC instrumentation can actually perform this task.

The Naval Postgraduate School Department of Meteorology and the Naval Research Laboratory Marine Meteorology Division (NPS/NRL) are participating in MORIAH acquisition specifications by providing METOC system validation, verification, and integration for meteorological instrumentation and data processing. This thesis presents an evaluation of the performance of a prototype MORIAH (SEAWASP) system deployed on two AEGIS ships for eight months (May to December 1998). The ships' deployment covered the Atlantic Ocean, Mediterranean Sea, and Arabian Gulf. The system performance evaluation focuses on two separate issues: reliability of system operation and accuracy of sensor measurement.

III. ATMOSPHERIC SURFACE LAYER REFRACTIVITY (EVAPORATION DUCT)

A. REFRACTIVITY CONCEPTS AND BASICS

Atmospheric electromagnetic (EM) refraction modifies the direction of propagation of a wavefront. The ray describes the wavefront direction and is normal to the wavefront. Refraction is described by the index-of-refraction, n, and defined by the ratio of wave speed in free space (c) to wave speed in the medium (v), Eqn. (1). EM rays bend toward regions of slower wave propagation speeds or higher n. Gradients in the index of refraction across the propagation path cause refraction or ray curvature effects. For most conditions, the primary gradient of the index of refraction affecting operations is that occurring in the vertical (dn/dz), where z is height.

Since the normal value of n for the atmosphere is close to unity, a more convenient and useful parameter describing refraction is used, refractivity N. Eqn. (2) is the relationship between the index-of-refraction (n) and the refractivity (N). For microwave frequencies and below, Eqn. (3) (Bean and Dutton, 1968) relates N to the routinely measured atmospheric variables of absolute temperature (T), partial pressure of water vapor (e) and total atmospheric pressure (P) where T is in degrees Kelvin, and P and e are in millibars.

$$n = \frac{c}{v} \tag{1}$$

$$N = (n-1)\times 10^{6}. \tag{2}$$

$$N = 77.6\frac{P}{T} - 5.6\frac{e}{T} + 3.73\times 10^{5}\frac{e}{T^{2}} \tag{3}$$

Most applications of EM refractivity consider propagation between two points on the earth where the earth's curvature is important. A useful parameter is modified refractivity M which is the refractivity corrected for the gradient that would cause the ray to propagate parallel the earth's surface. This

refractivity gradient is approximately – 0.1568 km^{-1}. Eqn. (4) is the expression for M where r_e is the earth's radius ($\approx 6.378 \times 10^6$ m) and z is the height above the surface in meters.

$$M = N + \frac{z}{r_e \times 10^{-6}} = N + 0.1568z\,. \tag{4}$$

In a standard atmosphere (Bean and Dutton, 1968), the refractivity decreases with height. Under normal conditions, the behavior of the M profile is more complicated. The vertical gradients of N or M (dN/dz or dM/dz) define the four general refractive categories listed in Table 3.1. Radar propagation is determined by the vertical gradient of M (dM/dz) rather than its absolute value. When dM/dz = 0, the EM ray curvature is equal to the earth's surface; when dM/dz > 0, EM rays curve away from the earth's surface; when dM/dz < 0, EM rays curve downward toward the earth's surface. If a negative dM/dz layer extends to the surface, then EM rays are trapped between the surface and the top of the layer, a phenomenon known as a surface duct which significantly affects surface-based transmitters. The general effect of dM/dz is described by the propagation conditions listed under *Distance to Surface Horizon* in Table 3.1.

B. EVAPORATION DUCT

From the previous Eqns. (2) and (3), a trapping layer requires that air temperature increase with height and/or humidity decrease with height at a significant rate just above the surface. Since the relative humidity above the ocean generally decreases rapidly from a value of nearly 100% at the surface, a thin trapping layer usually exists over the ocean. These ducts are known as 'evaporation ducts' because the humidity gradient leading to the formation of the duct is associated with evaporation from the ocean surface.

An M profile leading to a typical evaporation duct situation is illustrated in Fig. 3.1. The top of the trapping layer, where dM/dz = 0, is referred to as the 'evaporation duct height'. Since dM/dz < 0 below this level, it is the level of the minimum value of M. The evaporation duct height acts like a waveguide.

EM waves propagate over the ocean surface for much greater distances than expected, over the horizon. For these reasons it is obvious that information on the presence and height of the evaporation duct is critical to properly assess EM propagation conditions near the ocean surface.

C. BULK EVAPORATION DUCT MODEL

The capability to make continuous direct measurements to determine the presence and height of evaporation ducts is not feasible in an operational environment. Direct determination would require multi-level fixed sensors starting near the surface and extending to heights that cover the normal evaporation duct's vertical extent. The common evaporation duct height range is from 2 to 40 m. Mean bulk measurements (wind speed, temperature, humidity and pressure) at a reference height (deck-level) and surface temperature will be obtained continuously onboard USN ships with systems such as SEAWASP.

Bulk models for the surface-layer allow the use of mean measurements to estimate temperature and humidity which are needed to calculate near-surface refractivity profiles. The refractivity profile is then interpreted for the presence and height of evaporation ducts. Empirically formulated models that relate the profiles to surface fluxes, so-called flux-profile models, are used to relate bulk measurements at a single level in the atmosphere and the surface. Monin-Obukhov Similarity (MOS) theory establishes the approach for the models. According to MOS theory, conditions are assumed to be horizontally homogeneous and stationary. The turbulent fluxes of momentum, sensible heat and latent heat are assumed to be constant with height in the surface layer. In practice, the surface layer is regarded as the region adjacent to the surface where the fluxes vary by less than 10%, generally extending upward to a height of roughly 20 to 100 m.

This thesis uses the Naval Postgraduate School (NPS) adapted LKB (Liu et al. 1979) bulk surface-layer scaling model (Frederickson et al. 1999) within the MOS approach to determine the evaporation duct height from the near-surface M profile. The NPS model is also similar to a version described by Babin et al. (1997) which was formulated directly from the LKB. There are several important differences between the NPS model and that described by Babin et al. The NPS model's integrated profile

functions for stable conditions are different from the Businger-Dyer type functions used by Babin et al. The use of the new functions allows convergence of the model solution in many highly stable, low wind speed conditions in which the Businger-Dyer functions would result in non-convergence. The model also uses a new form for the thermal roughness Reynolds number R_θ, which, unlike the discrete original LKB functions, has no first order discontinuities and is also much simpler to implement.

The NPS approach is to compute modified refractivity (*M*) profiles and determine the evaporation duct height directly from this profile. Babin et al. (1997) used an iterative method to determine the evaporation duct height. The profile approach has the advantage that the *M* profiles themselves provide operational users with useful EM propagation information. The method also avoids the possibility that the iteration for duct height will not converge.

The NPS model is based on the full definition for the refractivity (*N*) whereas the Babin et al. (1997) model uses an approximate expression that neglects the complete vapor pressure contribution. While this term is generally small, in certain stable conditions it can modify the vertical *N* profile enough to significantly change the evaporation duct height (Frederickson et al. 1999).

Finally, the NPS methodology includes operational checks for valid input data ranges and indicates no solution is possible when the data is outside of the valid ranges. This avoids the possibility of the operator receiving erroneous model solution based on obviously bad input data.

Figs. 3.2, 3.3, and 3.4 show the NPS bulk evaporation duct model derived heights for several different environmental conditions. Each figure shows the evaporation duct height solutions (colored lines) based on fixed sea-surface temperature (SST) and wind speed. The solution (colored lines) for each figure will depend on the relative humidity and air-sea temperature difference (Tair – Tsea ≡ ASTD) value where ASTD defines the surface-layer stability condition. Negative ASTD is unstable and positive ASTD is stable. The ambient wind condition is different for each figure. Fig. 3.2 shows the light wind case (2 m/s), Fig. 3.3 the moderate wind case (6 m/s), and Fig. 3.4 the strong wind case (10 m/s). Notice that for stable conditions in light winds, the solution for height where $dM/dz = 0$ is not as distinct.

D. ADVANCED REFRACTIVE EFFECTS PREDICTION SYSTEM (AREPS)

The use of an accurate performance model was one requirement presented earlier for accurate assessment of environment effects on weapon system performance. A propagation model that predicts EM field strengths based on refractive conditions fulfills this requirement. The propagation model used for analyses in this study was the Advanced Refractive Effects Prediction System (AREPS), developed by the Atmospheric Propagation Branch at the Space and Naval Warfare Systems Center (SSC), San Diego. The model is a combination of Fourier spectral and geometric solutions to the EM propagation equation designed for accuracy and speed in an operational environment. AREPS computes and displays a number of tactical decision aids. These are airborne and surface based radar probability of detection, electronic surveillance measure (ESM) vulnerability, UHF/VHF communications, simultaneous radar detection and ESM vulnerability, range-dependent raytrace, and a surface-search range table. All decision aids are displayed as a function of height, range, and bearing. Detection probability, ESM vulnerability, communication, and surface-search range assessments are based on EM system parameters stored in a user changeable database. Paths containing land features depend on terrain either obtained from the National Imagery and Mapping Agency's (NIMA) Digital Terrain Elevation Data (DTED) or specified by the user.

Calculations performed in AREPS depend on atmospheric refractivity data derived from observations provided by radiosondes or other sensors. AREPS uses the Advanced Propagation Model (APM) to calculate range-dependent EM system propagation loss within a heterogeneous atmospheric medium over variable terrain, where radio-frequency index of refraction is allowed to vary both vertically and horizontally while accounting for terrain effects along the path of propagation.

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IV. SEAWASP SYSTEM DESCRIPTION

SEAWASP is the METOC system of MORIAH in discussions related to the latter's performance. The following system description will describe SEAWASP as the METOC measurement and performance assessment component of MORIAH. In the actual system design under existing programs, SEAWASP includes tactical decision aids to demonstrate the feasibility of in-situ estimation of radar and weapon system performance.

SEAWASP has two primary systems: Environment Characterization (EC) and Radar Performance Assessment (RPA). The EC system acquires observations of the local environment and produces a modified refractivity profile (dM/dz) from the surface to 350 m altitude that is automatically sent to the RPA system. The RPA uses the refractivity profiles to compute and display AN/SPY-1 radar performance for live radar settings and selected target options. Fig. 4.1 is a functional overview of the SEAWASP System.

Basic components for the EC system are the port and starboard meteorological masts (met masts), rocketsondes, floatsondes, and a data acquisition / processing system. Each met mast has sensors to measure air temperature, relative humidity, and wind speed / direction at a reference height of nine meters above the sea surface. Fig. 4.2 shows the port and starboard met mast, and Fig. 4.3 shows the met instrumentation box. The SEAWASP starboard met mast also includes a Global Positioning System (GPS) antenna / receiver, compass, and sensors for atmospheric pressure and infra red (IR) Sea-surface temperature (SST). The port met mast incorporates a sonde receive antenna for rocketsonde and floatsonde data. In addition to the IR SST, a separate sensor measures seawater inlet temperature (SWIT) for the AN/SPY-1 radar cooling water. Table 4.1 is reproduced from JHU/APL Hardware Technical Description for the METOC Sensor Equipment and lists the differences between SEAWASP and MORIAH met mast architecture and configuration.

Because the models require METOC parameters representing the ambient environment not contaminated by the vessel, an important aspect of the SEAWASP design is the placement of port and starboard met masts. The ship's hull can cause significant changes to the ambient air temperature, relative

humidity, and wind speed. Poor sensor placement will reduce measurement reliability and lead to poor performance predictions (Blanc, 1986).

Based on observations and considering possible compromises with operational ship configurations, the SEAWASP met masts are mounted aft of the Vertical Launch System (VLS) deck. Valid uncontaminated measurements are obtained when the relative wind speed across the sensor is above 2 knots and wind direction relative to ship's longitudinal axis is between 015-170 degrees for starboard sensors and 190-345 degrees for port sensors. In an effort to further improve the quality of the atmospheric measurements, JHU/APL increased the minimum relative wind speed criterion to four knots for this deployment.

SEAWASP acquisition control algorithms edited data according to several criteria. The editing was designed to select the most representative values of environmental parameters. These parameters were measured by or calculated from measurements of more than one sensor. The SEAWASP acquisition control system enables the criteria to be modified with the system menu. For the existing met mast location arrangement, the dual sensors have been found to supply satisfactory data for 75% of the time on average (Rowland, et al., 1997). Verification and evaluation of this hypothesis is a primary objective of this thesis evaluation of the system's operational performance.

The data acquisition program controls the recording and calculation of parameters. For the measured parameters, the computer continuously evaluates whether relative wind speed and direction for starboard or port met mast meet acceptance criteria. If criteria are satisfied for a designated fraction of a 5-minute period on one met mast, data are considered valid or uncontaminated by the ship's hull and a 5-minute averaged value is calculated. In its current configuration, the criterion for an acceptable fraction of a 5-minute period is 60%. Otherwise, no average is calculated for that period and the record is "blanked" with a null value, and the evaluation cycle restarts. After three invalid consecutive 5-minute cycles, the system will uses less restrictive quality control parameters. The less restrictive criteria selects the met mast with the highest relative humidity and lowest air temperature. The conceptual basis for this assumption is that the ship hull heats the air and lowers relative humidity. IR SST, ship GPS course, ship position, and relative wind vector are also averaged for the 5-minute period. For rocketsondes (air

temperature, relative humidity, pressure) and floatsondes (air temperature and relative humidity at 2 cm, sea temperature at 1 cm depth) are recorded at 1 Hz.

In the data acquisition program, the ship's true heading is based on SEAWASP's own compass heading corrected for local magnetic declination at current ship position and changing magnetic anomalies caused by steel-hulled vessel. The correction algorithm uses position obtained from the GPS receiver. Corrected compass data along with ship heading from GPS receiver and average relative wind vector are used to calculate true wind direction and speed.

Two different techniques are required to describe the profile from the surface to 350m altitude. The lower region (surface to altitude in tens of meters) is modeled using time-averaged bulk meteorological measurements. The near-surface modified refractivity including the evaporation duct profile uses the averaged ship data and sometimes the floatsonde data. Above the surface layer, to an altitude of 350 m, rocketsonde pressure, temperature, and relative humidity data obtained during the parachute descending phase are used with the altitude calculation to describe the vertical profile of modified refractivity (dM/dz). These two profiles are merged to produce a single profile for the radar performance assessment.

The basic components for the RPA system are the propagation model (TEMPER or AREPS), AN/SPY-1 radar performance model FIRMTRAK, server programs which control data flow and model execution, and a Human-Machine Interface (HMI). SEAWASP interfaces with the AEGIS system since its radar configuration is not totally controlled by the operator with some system settings automated by the combat system. Based on the radar's live settings, real-time performance assessments are displayed to the operator via the HMI.

The EC and RPA systems continuously measure the environment and provide real-time performance predictions based on the actual environmental conditions. The importance of a continuous measurement system is easily demonstrated by considering observed temporal variability of the evaporation duct. This will be shown in the next section with an example from the operational data set, where Anzio's SEAWASP system did not update for a 2-hour period and failed to depict a significant increase in evaporation duct and radar coverage.

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V. CONTINUOUS METOC MEASUREMENT

A reason for continuous measurement objectives in MORIAH is that surface ducts including evaporation ducts have temporal and spatial scales of variation which conventional numerical weather prediction models and METOC measurement instruments have great difficulty resolving. The tactical contribution from knowing these changes in ducts can be significant, but SEAWASP is the only operational system which has this measurement and analysis capability. A case study from a SEAWASP operational deployment in the Arabian Gulf illustrates the importance and capability of this continuous METOC measurement system.

Fig. 5.1 shows the bulk model evaporation duct derived heights for the Anzio and Cape St. George on 16 November 1998. From 00Z to 04Z, SEAWASP measurements and evaporation duct height estimates yielded similar refractive conditions for both ships with duct heights approximately 7 m. Shortly after 04Z, the SEAWASP acquisition program on Anzio did not provide reliable information for almost 2 hours (0600Z). During this period, the Cape St. George system continued to provide reliable information and showed duct heights increasing to approximately 20 m. The gap in information from the Anzio does not imply fault with Anzio or the SEAWASP system. Rather, it indicates the continuous nature of observations necessary to depict changes in the surface refractivity conditions.

The critical importance of depicting this change can be quantified by the gain in radar coverage as the duct height increases between 04Z and 06Z. This is accomplished by using the 04Z and 06Z Cape St. George surface layer *M* profiles, evaporation duct profiles, with the AREPS radar propagation assessment model. Figs. 5.2 and 5.3 are AREPS propagation loss diagrams for a theoretical radar system operating at 1000 MHZ and 20 m height above the water. The region bounded by the black propagation loss line and red 90% Probability of Detection (Pd) line depicts the analyzed range (km) where a small radar cross section target can be detected with 90% probability. Fig. 5.2 is the propagation loss for refractive conditions at 04Z and shows that there is a gap in 90% Pd coverage approximately 30 km downrange and maximum expected coverage out to 80 km. Fig. 5.3 is the propagation loss for refractive conditions at 06Z. The propagation conditions significantly improve with continuous 90% Pd coverage out to 100 km. This

represents a 20 km gain in the maximum expected coverage without a null zone from the ship to the maximum range. For a target flying at mach one, 20 km provides an additional 60 seconds.

This clearly illustrates the vital role a reliable continuous METOC measurement system can make in the optimal configuration of the AEGIS Weapon System. A point is made that these results were obtained using SEAWASP data collected from two operational ships patrolling in the Arabian Gulf where horizontal variations may occur and land masses may be within 100 km of the vessel. However, if the Cape St. George system failed to update during this period the preceding disclaimer is significant. From this case study, a MORIAH system operating at full capacity would provide the optimal radar configuration for gains associated with observed change in ducting conditions. A continuous measurement system will also depict important changes in the environment necessary for knowing how to manage limitations imposed by the environment.

VI. PROCEDURES

A. DATA CHARACTERISTICS

This study of system performance addresses three issues which determine the format and selection of the data: accuracy, reliability, and integration of measured data with a bulk evaporation duct model.

Determination of system accuracy usually requires a comparison of a system to a reference. In an operational environment, normal ship operations do not allow laboratory type testing of the ship sensor accuracy against a reference sensor. Laboratory type testing would be accomplished by having a vessel with mounted sensors spending a sufficient amount of time, under a wide range of conditions, operating near a buoy or tower mounted with reference SEAWASP sensors. This method is not practical within an operational deployment due to cost and vessel availability for research projects. It was determined that meaningful sensor comparisons could also be conducted by deploying two identical systems on two ships that operate in close proximity of each other.

Operational ship data can be evaluated for accuracy by comparison of data from identical type of sensors, mounted and configured in the same locations, and when ship positions are within a predetermined distance criteria. The requirements are 1) both systems are calibrated at the beginning of deployment 2) the change in each system are uncorrelated after calibration and 3) the RMS difference is a measure of uncertainty in system performance that can be used for interpretation with regard to performance requirements.

The distance criteria selected were 10 km or less for the ORD requirement evaluation and 5 km or less for the AEGIS requirement evaluation. These distances were based on two primary considerations. First, the difference that could be expected in average atmospheric parameters with a given separation. Second, the number of observation pairs necessary to establish statistics for evaluating accuracy and reliability requirements.

An evaluation of system reliability requires data sets with long time duration. Operational deployments usually satisfy this criterion. SEAWASP deployment data sets with long time duration exist

from deployments of Naval Station Norfolk based CG's since 1998, i.e. USS Leyte Gulf (CG 55), USS Port Royal (CG 73), USS Lake Erie (CG 70), USS Anzio (CG 68), and USS Cape St. George (CG 71). There are several satisfactory data sets and NPS has already used one in a study of merging operational measurements with satellite derived data which was during an annual summer exercise, BALTOPS97 with the Anzio and Cape St George.

Based on this discussion, SEAWASP deployments on the Anzio and Cape St. George from May to December 1998 were selected for the instrument and system performance evaluation. Figs. 6.1 and 6.2 show the ship tracks for this deployment, and Table 6.1 lists ship positions and dates.

Fig. 6.1 shows the ship tracks during the entire cruise indicating portions when data were available. Both ships departed from Norfolk, but they had different routes and schedules for their transits to the Arabian Gulf. Anzio did not have a continuous data set for her deployment, and the data initializes her position in the Mediterranean Sea in early September with another data gap from 15 September to 25 October 1998. The first missing Cape St. George track arises because of a missing data disk, and the second gap was due to hardware failure from a large power surge. Fig. 6.2 shows the ship tracks while the vessels were in the Arabian Gulf. Of the two vessels, the Cape St. George spent the most time in the Arabian Gulf with several passages through the Straits of Hormuz during the deployment. Cape St. George first entered the Arabian Gulf in early September. Anzio arrived on-station in the Arabian Gulf in November and spent a total of 8 days in the Arabian Gulf during the middle of November. Both ships left the Arabian Gulf in late November and transited in close proximity of each other until their December arrival back in Norfolk.

B. AVAILABLE METOC DATA

The expected accuracy and reliability were based on data from SEAWASP sensors listed with MORIAH sensors Table 6.2. MORIAH will include more than those listed in this table. Table 6.3 shows the continuous measurement capability, supplemental sensors, and scope of algorithms planned for MORIAH. The column headers are the shipboard METOC sensor capability that the planned MORIAH

system will provide, and the row headers are the algorithms that the system will use to prepare the acquired data for operational applications. The limitations of these evaluations relative to MORIAH's present, near-term, and future components / systems are shown in Table 6.4. An important consideration for this accuracy and reliability study is that SEAWASP is the prototype for MORIAH. Therefore, collection and real-time processing for SEAWASP may not correspond exactly to the analyses / interpretations on MORIAH's operational performance. For these analyses/interpretations, selection and processing of SEAWASP obtained data required considerable design and execution tasks to optimize its interpretation for MORIAH.

C. DATA PROCESSING

The operational deployment data sets required organization and formatting, i.e. restructuring, with various averaging times and with both unedited (raw) and validated (averaged) data being available. Table 6.5 lists these files and their sampling / recording frequency. Most of the effort arose because the planned and performed evaluation were based on time series and paired data comparisons. Data was stored in separate data files which had to be combined into a single/merged data set.

SEAWASP's data acquisition is designed to provide information for an event (i.e. target acquisition). Therefore, the file architecture is event driven rather than time series driven. This led to a file structure in which raw met mast METOC data are recorded and stored every 10 seconds in a unique file. The raw met mast data which is averaged over a 5-minute period are stored in another file. Therefore, SEAWASP data files are unique for each 10-second period (raw/instantaneous) and 5-minute period (averaged) period. Each file included a GPS location and observation time associated with the effective observation time. This file architecture / format was not immediately useful for time series or comparative evaluation in which information on data gaps and relationships of sequential values were being examined. An approach was designed and verified to perform the analyses from this unique operational data set that could be interpreted relative to meeting several aspects of the governing ORD and operational application. The general approach used to prepare the data for our evaluation is as follows.

1\.

Combine separate event files into continuous files according to type, such as average met-mast, rocketsonde, and catamarran.
Reformat file to process data for later pair comparisons or time series; one file becomes a record within a new file (time series).

2\.

Identify gaps according frequency/duration, caused by:
Data collection not occurring.
Data selection criteria not met, "blanking".

3\.

Merge the data from both ships: Cape St. George and Anzio.
Compute the distance between ships for comparisons selection; e.g. comparisons for: Vessel separations of 5 and 10 km.; For on-station or transit operations; and 10-second (raw) and 5-minute (averaged) data.

4\.

Evaluate selection criteria relative to increasing data acceptance.

5\.

Display results
Time series
Ships position
Paired data
Determine data validity/consistency.
Relate validated data to ship operation speed, location, station keeping, or transit.
Apply solar azimuth effects on warming of port or starboard side .

These steps led to several types of files used in the examination and are listed in Appendices C - F. These were used in many different comprehensive anlayses from which some results are discussed in the following sections.

VII. INSTRUMENT / SYSTEM PERFORMANCE REQUIREMENTS

A. MORIAH OPERATIONAL REQUIREMENTS DOCUMENT (ORD)

This thesis documents the performance of SEAWASP in operational conditions relative to MORIAH ORD specifications. The specified minimum (ORD Threshold) and optimum (ORD Objective) system and sensor performance values are listed in the ORD. The performance requirements are reproduced in Table 8.1. The ORD Threshold performance is the minimum acceptable performance level for the MORIAH sensors and system, and the higher ORD Objective level is the optimal target for performance.

B. AEGIS

SEAWASP's operational customer is the AEGIS operator who bases sensor and system performance on the accuracy and reliability of real-time assessments of atmospheric refractive conditions. The sensor accuracy analysis compares SEAWASP sensor performance with Dockery's (1997) support requirements for surface observations and evaporation duct height determinations and Blanc's (1986) guidelines for sensor limits of accuracy in estimating surface fluxes in a ship contaminated environment. Dockery specified that evaporation duct height determinations must be within 2 m for adequate operational support. Dockery's measurement and evaporation duct height determination specifications are the AEGIS requirements for METOC measurement accuracy. Table 8.2 lists Dockery's requirements and Blanc's guidelines. Evaporation duct heights uncertainties will be evaluated on the basis of Dockery's duct height accuracy requirement.

SEAWASP is designed to optimize the AEGIS Weapon System based on local measurements of the environment. Thus, the operational user is concerned with how often the system validates data for use in tactical applications. Baselines for this reliability performance are provided by observed and statistical analysis done by JHU/APL (Rowland, et al., 1996). AEGIS system reliability evaluation is compared

against JHU/APL baseline and requirement for minimum system update cycle of at least one-half of system total operation time (50%).

VIII. INSTRUMENT / SYSTEM PERFORMANCE ANALYSIS

A. ANALYSES BASED ON ORD REQUIREMENTS

ORD sensor accuracy specifications are expressed as acceptable differences (± values) from the actual condition. The method selected to evaluate measurement system accuracy is the comparison of simultaneous measurements made from identical systems aboard two ships operating within 10 km of each other. The comparative analysis is discussed in the *Procedures* Chapter VI. Root Mean Square (RMS) differences between measurements was then attributed to uncertainty in the measurements due to instrument variation or to local ship effects. The calculated RMS is compared directly to ORD Threshold and Objective sensor specifications in Table 8.1.

ORD system reliability specifications are defined by Operational Availability (A_0). A_0 is the ratio of the total usable time to the total possible operational time of the system. The system usable time includes both normal operation time and scheduled / unscheduled maintenance periods. No maintenance was required for this prototype MORIAH system. For the purposes of this thesis, the ship's total operational time extends from the period of the first SEAWASP data record to the last. The basis dates cover 05 Sep 98 to 10 Dec 98 for the Anzio and 27 May 98 to 21 Dec 98 for the Cape St. George. The basis dates are used to express the ship's total possible operational time as the number of mast average (5-minute) records. The total usable time is the number of mast average data records validated by the system. A direct comparison is made of the resulting ratio of mast average records with ORD reliability requirements in Table 8.4 to determine A_0.

1. Accuracy

The parameters in this analysis include air temperature, sea surface temperature (SST), atmospheric pressure, wind speed and relative humidity. Wind measured on the SEAWASP met mast is not intended to be the source of MORIAH wind measurements. The wind measurements are obtained only for a diagnostic purpose, to evaluate the quality of METOC parameters aboard ship.

The Anzio SEAWASP sensor suite did not provide IR SST, while the Cape St. George IR SST sensor was active only for system testing purposes. However, SST values from the AEGIS radar cooling seawater inlet temperatures (SWIT) were available from both ships. The normal operation of SEAWASP allows the use of either SST measurement, but the primary MORIAH SST measurement is intended to be IR. All calculations and analyses are based on SST derived from SWIT.

Table 8.1 and Fig. 8.1 provide results on observed system accuracy relative to the ORD requirements. These were based on comparisons when the ships were separated by less than 10 km resulting in a set of 1234 data points. Table 8.1 summarizes the MORIAH requirements and provides the SEAWASP sensor performance statistics. The RMS difference of the two sensor measurements and the correlation of the measurements characterize SEAWASP accuracy performance. The last two columns show the fraction of data meeting the criterion for separation of sensors which meet the ORD Threshold and Objective specifications. Fig. 8.1 displays the corresponding scatter plots for when ship separation is less than 10 km. Perfect agreement between ship measurements would yield a straight line with a positive slope of 1.00, intercept through the origin (0,0), and a correlation coefficient of unity for the two sets of measurements. The green line on each plot is the least square fit for the plotted points with slope, intercept (INT), standard error (SE), and coefficient of correlation (*R*) annotated on each plot.

Referring to Fig. 8.1, the scatter plots for air temperature and relative humidity, the least squares best fit lines, and the statistical correlation show a high level of performance and agreement. The root mean square (RMS) difference of the air temperature is 0.5°C and relative humidity is 2.38%. The slopes are the same with air temperature and relative humidity equal to 0.99. The *R* supports the slope with air temperature of 0.9996 and relative humidity of 0.9992. There is no indication of a bias for either sensor with the same y-intercept value of – 0.01. As expected, the last two columns show that a large percentage of the data meets the ORD Threshold requirements.

The SST and pressure results (RMS) do not meet ORD Threshold requirement; but they show good agreement based on the relatively low RMS difference and the correlation coefficient value being approximately 1.00. The SST RMS difference is 0.56°C and pressure is 1.45 mb. The SST ORD Threshold column shows that there is a large percentage of data which fits the ORD Threshold accuracy

requirement (97.33%). The pressure percentage that agrees with the ORD is significantly lower (29.42%). The slope of pressure shows the highest possible slope derived correlation with 1.00 and SST is slightly less with 0.93. The correlation coefficient of SST from both ships is 0.9979. The correlation coefficient of pressure from both ships is 0.9943. There is an indication of a bias for both sensors. The SST intercept is 1.86 and pressure intercept is – 0.90. SST bias is believed to result from a calibration difference between ships. Pressure correlation and slope indicate that this bias is not likely from a pressure gradient. Rather, the manufacturer's sensor error specification is large in comparison with ORD Threshold specification.

The wind comparison was based on vector averaged true wind observations. The wind data used in these comparisons were after the Anzio power surge outage. The calibration corrections were not reinstalled which resulted in a bias for the wind results. The vector wind RMS differences were 7.2 knots and 90.4° Azimuth, these differences exceed the ORD Threshold requirements. The scatter plot for winds and associated statistics shown in Fig. 8.1 show correspondingly low degree of correlation and agreement. The percentage of records which fulfill ORD Threshold requirements is also low. This unsatisfactory performance of vector winds is not deemed critical since the wind measurement is not the MORIAH intended measurement sensor. However, this is the primary criterion for the selection of the sensor mast, and this result indicates the degree of ship contamination of the wind field.

2. Reliability

The ORD system reliability specification, A_o (%) is the ratio of the total usable time to the total possible operational time of the system expressed in percent. Table 8.4 summarizes A_o results. The Cape St. George system A_o value of 97.8% meets the ORD Threshold requirement of 96.9 % and nearly meets the ideal ORD Objective requirement of 98.1%. The Anzio system A_o (55.7%) does not meet the ORD Threshold Requirement. This was due to loss of system due to ship power surge on 15 September 1998. JHU/APL personnel repaired the system and restarted measurement operations on 25 October 98. The outcome was an approximately 40-day loss in system usable time.

B. ANALYSES BASED ON SPECIFIC OPERATIONS (AEGIS)

The same general methods are used for determining SEAWASP performance as with the ORD requirements. Because of the more stringent accuracy criteria, the possible contamination by atmospheric spatial variability was reduced by using a 5 km separation criterion. Two comparative analyses are made with SEAWASP sensor performance. The single sensor comparison is made with Dockery's (1997) near term surface observation specifications with SEAWASP RMS differences. A comparison is also made with SEAWASP bulk model evaporation duct height determinations relative to Dockery's 2 m evaporation duct height accuracy requirement.

AEGIS reliability analysis uses the ratio of the total valid information time to the total usable time versus total usable time to total possible time. The total valid information time is the number of validated mast average records produced by the system. The total usable time is the same as the MORIAH ORD analysis.

1. Accuracy

AEGIS accuracy requirements for SEAWASP should meet the measurement specifications required by the most demanding or stringent mission requirement. The primary use of the SEAWASP system has been to provide EM support by the calculation of the evaporation duct which provides the basis for operational / AEGIS performance predictions. The performance prediction needs differ from the specifications of the ORD in that the former specifies a cross correlation of the parameters in addition to specifying parameter accuracy. This section analyzes SEAWASP accuracy performance in supporting the required evaporation duct height estimates to support radar propagation predictions with detection range errors less than 1 nm for low-altitude targets (Dockery, 1997). Individual sensor performance will be compared with Dockery's near-term surface observation requirements. A correlated sensor evaluation will be done through a comparison of the resulting duct height estimation.

As described in Chapter III, EM system propagation models such as AREPS and TEMPER (Kuttler and Dockery, 1991 and Dockery, 1995) depend on accurate descriptions of the atmosphere's near-surface refractivity profiles to reliably predict radar and communication system performance. Near-

surface refraction profiles that describe the evaporation duct profiles depend on profiles of temperature and moisture. These vertical profiles are estimated using models based on bulk aerodynamic scaling and single level measurements of air temperature, humidity, wind and SST.

The evaporation duct height is defined by the extremum of the refractivity profile, $dM/dz = 0$. The evaporation duct effect depends on the radar frequency. For example, an 11 m evaporation duct significantly influences a 10 GHZ (K band) radar while a 30 m duct is necessary to significantly affect a 1.5 GHZ (L band) transmitter. Propagation models require evaporation duct height estimates to be accurate within 2 m for adequate operational support (Dockery, 1997).

Air temperature, SST, and relative humidity sensor measurement differences given by Anzio and Cape St. George RMS differences, are presented in Table 8.2. Air temperature and SST RMS values of 0.47°C to 0.55°C are nearly twice that suggested by Dockery (1997), ±0.25°C. Air temperature RMS difference values are nearly 1.5 times larger than Blanc's (1986) limits of accuracy, ±0.3°C. The SEAWASP relative humidity RMS of 0.5% is much less than the 2% suggested by Dockery. Hence, Table 8.2 shows that relative humidity is the only key refractive parameter which performed within sensor accuracy limits for propagation assessments. The air-sea temperature (ASTD) parameters were also out of limits. Considering the relative differences between performance statistics for 5 km and 10 km data, RMS difference for air temperature and relative humidity decreased with the 5 km distance criteria, from 0.50°C to 0.47°C and 2.38% to 1.61%, respectively. The statistics and scatter plots for key refractive variables from this comparison based evaluation are shown in Fig. 8.2.

AEGIS analyses results also pertain to the evaporation duct. Fig. 8.2 shows the scatter plots and performance statistics for the evaporation duct parameters. Fig. 8.3 shows the scatter plot for bulk derived evaporation duct determinations corresponding to parameters in Fig. 8.2. The points are plotted in red and blue, and they correspond to simultaneous sensor measurements / duct height calculations. These were based on comparisons when the ships were separated by less than 5 km resulting in sample of 776 data points. The procedure for the accuracy analysis using Dockery's (1997) requirements is similar to the ORD accuracy analysis. The RMS difference and correlation of the two sensor measurements characterize

SEAWASP accuracy performance. The statistics used in the 10 km evaluation are also computed for the 5 km comparative analysis.

The red and blue color code is used in Figs. 8.2 and 8.3 to distinguish pairs for which the evaporation duct height is below and above 25 m with red indicating above 25 m. Bulk calculated evaporation duct heights from Anzio and Cape St. George data agree below 20 m but definitely start to diverge when the paired values increase above 20 m. The largest height differences are found above 25 m. This divergence seems to be related to definite trend for the Cape St. George to have larger ASTD values.

The conditions associated with duct heights above 25 m (plotted in red) are positive ASTD (air temperature greater than SST), low relative humidity (approximately 60%), and light to moderate wind speed (10 to 15 knots). These conditions are described as being thermally stable. With stable conditions, turbulent mixing is reduced and larger gradients can occur in the surface layer. The relationship between these gradients (the profile shapes) and the surface fluxes becomes more sensitive to the measured values determining the bulk parameters. The large difference of calculated evaporation duct height for these stable conditions is associated with this sensitivity since small differences between the ships' measured bulk parameters can lead to large differences in the evaporation duct height.

The paired evaporation duct height data points that show close agreement, denoted with blue symbols, correspond to conditions when the air is slightly cooler than the surface, unstable to neutral conditions. The sensitivity of the shape of the refractivity profile to bulk parameters under these conditions is less than for stable conditions so small differences in measuring the parameters do not cause large differences in the evaporation duct height. The different shape of refractive profiles that arise in stable and unstable conditions is illustrated in Fig. 8.4. The occurrence of the duct is determined by the vertical refractivity gradient (dM/dz). The uncertainty of the gradient implies that the gradient is near zero, $dM/dz \approx 0$, it is difficult to estimate the duct height. It is apparent that the duct height is more distinct on the profile when the air is cooler (unstable) than when it is warmer (stable) than the water.

The reason for the Cape St. George having larger evaporation duct heights when they are above 25 m seems apparent in Table 8.3. This table lists the range of values for each ship's parameter variation. The range of ASTD is similar for both ships but the Cape St. George ASTD has both higher minimum and

maximum values. There is a possible bias from the ship(s) affecting air temperature or SST measurements. That means that the Cape St. George could have measurements that indicated slightly more stable conditions which would lead to the higher bulk evaporation duct height.

Regression statistics for this calculated evaporation duct height comparison based on all pairs show an RMS difference of 5.30 m which exceeds the 2 m accuracy limit recommended by Dockery (1997). In unstable to neutral stability conditions corresponding to duct heights below 25 m, the RMS difference was 1.37 m which meets Dockery's recommendation. As noted, overall SEAWASP air temperature, SST, and wind measurements did not meet Dockery's accuracy requirements which resulted in unsatisfactory evaporation duct height determination.

2. Reliability

a. Continuity of Environmental Depiction

An important system performance reliability aspect not addressed by the ORD is the system's ability to accurately describe the environment in all conditions and the continuity of valid data to capture the significant changes in the environment. This is the Operational Data Reliability of the system, and it has to be evaluated on the basis of AEGIS requirements. For example, a user requiring environmental information for transmission off the ship once an hour has much different reliability requirements than one who has to continuously monitor the effect of the environment on the radar. For this evaluation of system reliability performance, reliability statistics are computed from the total possible data, valid data, and the data gaps (missing and invalid). Specific requirements for reliability are not specified by the ORD, but the minimum expectation for available data, in any scenario, should not be less than 50% of the total possible data and any gap should be short term.

The primary criterion used in determining data validity and met mast selection in SEAWASP is wind speed and direction. The secondary criteria is the combination of relative humidity and air temperature. The principal concern for met mast selection / data validity criteria is to have sampling of air which is not modified by the ship's superstructure. The relative wind requirements for acceptable data is that the relative wind speed across the sensor be greater than 2 knots and that the relative wind direction be within the predetermined ranges at the particular met mast: 015 – 170 degrees relative for starboard and

190 – 345 degrees relative for port. Airflow that meets these relative wind direction criteria is assumed to be free of ship influence. To further improve data quality of the atmospheric measurements, JHU/APL increased the minimum relative wind speed criteria to 4 knots for this deployment.

The relative wind based criteria was expected to lead to possible differences in reliability statistics for ships transiting (high speed, steady course) versus patrolling (low speed, frequent course changes). Depending on the true wind speed magnitude and direction, high ship speeds will frequently cause the relative wind direction to move towards the bow region (345 – 015 degrees) which is outside the acceptable range. Hence, for a high-speed transit in light wind conditions, more invalid records are expected than in a low-speed patrol with multiple course changes in moderate winds. The ship's direction and speed can have increasing impacts as the true wind speed decreases.

There are times when the wind direction and speed criteria does not resolve met mast selection / data validity. This condition when the general relative wind direction is from the bow (> 345 and < 015) or from the stern (< 190 and > 170), non-valid directions, for more than 60% of the 5-minute interval. Relative wind flow within this azimuth range is assumed be contaminated by the ship's hull or stern. For these times, a selection based on non-wind properties is used that compares met mast relative humidity and air temperature values. When wind direction criteria fail to select a met pole for valid data, the one met pole with the highest relative humidity and lowest temperature is selected as the one to provide valid data. SEAWASP's current configuration uses these secondary criteria after three consecutive 5-minute averages without valid wind criteria, i.e. the system selects data from the met mast with the highest relative humidity and lowest air temperature.

From SEAWASP performance documentation, we expect performance to fit the following profiles (Rowland et al. 1996):

1. SEAWASP configuration with dual met masts is expected to supply satisfactory data 75 % of the time on average.
2. If the ship is DIW and wind speed magnitude is above 2 knots, SEAWASP should provide good data 86% of the time.
3. If the ship is underway at a speed of 10 knots, we would expect good data 77% of the time.

Table 8.5 lists SEAWASP reliability performances according to four deployment phase categories associated with operations: 1) Total (System On to System Off), 2) 'System On' to On-station

(Norfolk to Arabian Gulf), 3) On-station (SouthWest Asia Operational Area), 4) Off-station to 'System Off' (Arabian Gulf to Norfolk). For the purpose of category selection for each ship, the on-station period commences when the ship crosses the longitude for the Straits of Hormuz. The Transit to CONUS begins when the ship crosses the longitude for the Straits of Hormuz for the transit back to CONUS.

The Records column in Table 8.5 shows numbers of records that determined the reliability statistics as total, expected, actual valid 5-minute records. The reasons for the actual record count being less than total were described earlier. The valid number of records is less than the actual recorded when the selection criteria is not met.

The first percentage value, i.e. 56% for Anzio 9/05-12/10 period, represents ORD operational availability (A_0) which is not pertinent to AEGIS Requirements. The second percentage value relates to AEGIS Requirements and it is the Operational Data Reliability since it is determined by the ratio of total data records that passed validity criteria and the number of expected records for the specified period. The *Data Gap* columns show the number of periods that are either missing records or contain invalid data for the specified length of time (i.e., ≤ 3-hours). The minimum duration considered for gaps is greater than 15-minutes. Fifteen minutes equates to three 5-minute QC cycle intervals without validated data which is assumed to be significant in an operational environment. This is supported by Rogers (1994) study of temporal or spatial variability of ducts in the coastal environment where 15-minute of time lag from last environmental update could produce as much as 4 db difference in standard error of received signal level.

From data covering the *Total Period* in Table 8.5, SEAWASP's Operational Data Reliability is less than baseline expectations of 75% suggested by Rowland (1996). For data obtained from the SEAWASP deployment, we expected the performance reliability to meet the baseline expectation of 75%. Table 8.5 *Total Period* Operational Data Reliability statistics list Anzio performance at 28% and Cape St. George at 49%. For the transit phases when ship speed is consistently above 10 knots and wind conditions represent a wide variety of conditions (Atlantic, Mediterranean, Red Sea), performance reliability for both ships was around 50% which is still significantly below the expectation of 75%. The best baseline performance reliability for the on-station phase is an average of the ship DIW and transit

baseline which is 81.5%. On-station performance reliability showed the highest contrast between expected (75%) and actual; 38% for Anzio and 47% for Cape St. George.

System reliability with regard to continuity is described by the duration of the data gaps (no data / invalid data). Table 8.5 also shows the distribution of data gaps lasting longer than 15-minutes. Data gaps are for either no data which are missing records due to system maintenance or data records flagged by a '-99' signifying invalid data. Only SST SWIT data is not blanked by the invalid data flag (-99) since it is not a met mast measurement. In this thesis, data gaps defined by no data are assumed to be caused by manual intervention / maintenance or addressed by the previous discussion of performance reliability, A_o, relative to the ORD. All deployment phase categories in Table 8.5 have larger numbers of short term than long-term gaps. Long-term gaps are considered to be columns covering the periods greater than one hour. Data gaps lasting 15-minutes may be considered acceptable in view of the current met mast selection / data validity configuration. However, long-term gaps approach the limit of acceptable performance based on the temporal scales of variability in coastal environments. In general, the data gap distribution obtained from this operational data set was an expected result since short term conditions of invalid conditions are more probable than long term conditions in any given period.

In any operational environment, data reliability should not be less than 50%. Lower reliability levels will not provide enough descriptions of the environmental conditions to update radar performance assessments for the majority of an on-station period. In general, the statistics shows a very significant issue with regard to SEAWASP performance in an operational environment and the system's ability to assess real time changes in propagation conditions. It is important to note that these unfavorable results regarding reliability exist even though the ORD Threshold and Objective requirements are met.

Even if overall lower performance relative to baseline expectations cannot be avoided, the relative performance of SEAWASP should be higher in the environment where the hostile threat is highest. The on-station performance shows the lowest amount of valid data produced for system analysis. Possible methods for improving overall and relative performance can be identified by further examinations of the met mast selection / data validity criteria. The following analyses addresses improvement of reliability performance through modification of this criteria.

b. Improving Operational Data Reliability

AEGIS reliability statistics show that environmental updates are not validated for the system to produce real time performance assessments for the majority of the ship's deployment. Also, the relative performance of the deployment phases reveals that on-station performance is significantly lower than transit performance. The combination of these factors highlights that Operational Data Reliability is a critical issue. An analysis of SEAWASP's data selection algorithm leads to a modification of existing criteria which can significantly increase this performance.

SEAWASP uses relative wind as the primary criteria and relative humidity / air temperature as the secondary criteria for determining data validity. In data validation, three consecutive 5-minute intervals of invalid relative wind criteria must pass before the secondary relative humidity / air temperature criteria is applied. On the third consecutive invalid 5-minute interval, the relative humidity and air temperature criteria is applied. The system determines if one met mast had both the highest relative humidity and lowest temperature average. Data from the met mast with highest relative humidity and lowest temperature is considered valid. The following analysis shows a significant difference in performance reliability is obtained if the relative humidity / air temperature criteria is used whenever relative wind requirements are not met.

Table 8.6 is similar to Table 8.5 and has statistics for performance reliability for both ships for the month of November. November was chosen for this extended analyses on increasing reliability since it represents a mixture of transit and on-station periods. The level of performance is similar, except in a few cases, to those in Table 8.5 for the on-station period which is approximately 40% for both ships. Table 8.7 shows the expected performance gains by applying the modified selection criteria to the corresponding instantaneous data set for each met mast. Because several numbers and pairs of numbers appear, additional information on the format is provided. Each row in the Table 8.7 is for the particular Zulu day in November. The top line of numbers in each row pertains to the port met mast and the bottom numbers pertain to the starboard met mast.

IX. SUMMARY AND CONCLUSION

This section provides summaries of results that were based separately on the MORIAH ORD and specific operational (AEGIS) requirements. The summaries and conclusions are based on the performance of both the deployed sensor suites and validating / editing algorithms. Conclusions will be presented that relate to implications of analyzed accuracy and reliability with regard to an operational instrument / system evaluation.

A. MORIAH ORD

1. Accuracy

RMS difference values in Table 8.1 show that validated 5-minute air temperature and relative humidity values met ORD Threshold requirements for accuracy but pressure and SST did not. SEAWASP wind performance is not considered here because SEAWASP (met mast) will not be providing operational wind values in the final version of MORIAH.

The compliance of air temperature and relative humidity RMS values with ORD accuracy requirements is considered to be a very positive attribute for the SEAWASP sensor performance and the validating / editing algorithm. This is an expected result based on the higher priority of refraction description objectives placed on SEAWASP over conventional METOC system requirements which served as a framework for the MORIAH ORD.

The SST RMS values exceeding ORD requirements is not considered to be serious since 1) RMS difference (±0.56°C) is relatively close to ORD specifications (±0.5°C), 2) the relatively close agreement between ship measurements is supported by the scatter plot in Fig. 8.1 and 3) the percentage of SST data which met ORD Threshold requirements is high, 97.33%. However, a significant SST result is the bias revealed in the Fig 8.1 with SST regression intercept equal to 1.86. Such a bias in conjunction with a regression slope near 1.00, means the Cape St. George's sensor yielded lower SST's due to a calibration

change during deployment. The importance of the air-sea temperature difference (ASTD) in surface flux calculation and models for near-surface refractive profiles makes in-situ calibration a critical issue.

Pressure RMS difference values exceeded the ORD requirement which is also concluded as insignificant since this can be resolved by available sensors with smaller uncertainty specification. Examination of pressure accuracy results reveal that simultaneous ship measurements were in close agreement based on the regression slope (1.00), intercept (– 0.90), and correlation (0.9946). The RMS difference values cannot be explained by time varying sub-synoptic environment or ship influences. The combined effects of sensor accuracy specification and inherent errors in comparing operational ship sensors are used to explain validated pressure values not meeting the ORD requirement. The pressure sensor manufacturer specification is ±0.05% which equates to ±0.5 mb uncertainty for 1000 mb conditions. This sensor specification uncertainty is 50% of the ±1.0 mb ORD Threshold accuracy which is considered a large initial uncertainty, independent of operational influence. Also, slight differences in calibration may exaggerate this level of precision to fail ORD accuracy specifications.

2. Operational Availability (A_o)

A_o evaluation showed that the Cape St. George A_o (97.8%) met the MORIAH ORD Threshold A_o requirement (96.9%), but the Anzio A_o (55.7%) did not. The reason for the Anzio low operational availability was a large power surge that also caused hardware failure on numerous ship systems. Without this interval, the system would have passed this ORD Threshold A_o. It is believed that in a normal operation deployment, MORIAH logistics supplied onboard replacement components would have been used to have the system on-line soon after the event.

B. OPERATIONAL (AEGIS) REQUIREMENTS

1. Accuracy

Results on meeting AEGIS accuracy requirements addressed determination of the near-surface refractivity profile, described by the evaporation duct height. AEGIS documented sensor accuracy requirements and evaporation duct uncertainty requirements by Dockery (1997) served as the basis for

evaluation. RMS difference values for relative humidity met requirements, but air temperature and SST RMS differences were two times too large. A significant result of the analyses for the operational accuracy was the regression determined bias in SST which affects the ASTD. The ASTD is an important factor in establishing near-surface refraction profile properties.

Differences in evaporation duct heights between the two ships were related to ranges of ASTD. The multi-variable determined evaporation duct height comparisons showed agreement between two ships during unstable and neutral ($T_{air} \leq T_{SST}$) conditions. However, calculated duct heights diverged in low wind, low humidity, and stable ($T_{air} > T_{SST}$) conditions. This also corresponded to times when evaporation duct heights were above 25 m. Disagreement of evaporation duct height in the stabile regime was consistent with sensitivity of flux-profile bulk models to bulk inputs. High evaporation duct heights occur with low humidity and low mixing. With stable conditions and low wind speeds, turbulent mixing is low and small changes in the ASTD can produce large changes in evaporation duct height.

The regression results indicated lower Cape St. George's SST which caused the Cape St. George's ASTD to be more positive resulting in bulk model derived higher duct heights. This result was concluded to be important in view of current naval operations in coastal regions where relative dry, warm air from land frequently flows over cooler water.

2. AEGIS Operational Data Reliability

The MORIAH ORD A_o does not address reliability in the context critical to the support of specific operations, i.e., providing real-time propagation assessments. This analysis shows that SEAWASP did not provide sufficient availability of validated data for continuous propagation assessments. Anzio availability of validated data was 38%, and Cape St. George was 47%. During transit the availability for both improved to approximately 50%. A significant result is that the overall Operational Data Reliability was only near 50% and on-station performance was lower than transit performance.

The analysis of SEAWASP mast selection algorithm led to the modification of existing criteria to significantly increase AEGIS Operational Data Reliability based on validated data. Significant gains (25%) in validated data occurred by considering the relative humidity / air temperature criteria for every invalid

wind record. A definitive measure of the degradation of relative humidity and temperature values was not accomplished.

X. RECOMMENDATIONS

MORIAH is a system now in acquisition. This study is the first performance evaluation of the system and it was performed on a prototype system because the version of MORIAH that will be operational is still being proposed by industry. The following recommendations are those arising from this first look at MORIAH-type data.

1) Evaluate final MORIAH system using operational data. The present evaluation, in a realistic operational environment, highlighted performance characteristics which would not have been detected under more controlled conditions.

2) Evaluate diurnal effects on system performance. The present evaluation was limited and did not analyze other effects such as diurnal influences. A detailed evaluation should be conducted for diurnal contamination of sensor measurements.

3) Check temporal consistency of METOC data. MORIAH is designed to depict refractive conditions as described by the local measurements from met masts, NDWMIS, floatsondes, rocketsondes, SWIT, and IR observations. The met mast selection / data validity algorithms produce data files that meet this purpose but the algorithms do not make use of past conditions to support data quality control. Quality control requires some degree of correlation of present observations with past observations and expected conditions.

4) Explore cross-sensor calibration issues. Evaluations of SST showed a systematic / constant bias. This shows the importance of accurate sensor calibration in applications such as evaporation duct modeling, where differences of observations by different instruments can be critical.

5) Evaluate sensor performance on other surface combatants. This evaluation and other SEAWASP deployments have all been analyzed for Ticonderoga class cruisers. Since Arleigh Burke class ships will have the same MORIAH METOC requirements, a separate evaluation should be conducted for this hull. Ship contamination is significant and different results are expected for each hull.

6) Refine met mast selection criteria. SEAWASP's Operational Data Reliability showed less than 50% valid data for on-station period, and on-station performance was worse than transit performance. Even though more valid records arose from modified relative humidity and air temperature criteria, no proof was shown that the same quality data was produced.

APPENDIX A. TABLES

Refractive Condition	d*N*/dz	d*M*/dz	Distance to Surface Horizon
SubRefraction	> 0 km^{-1}	>> 157 km^{-1}	Reduced
Normal	0 to 79 km^{-1}	> 157 km^{-1}	Normal
SuperRefraction	-79 to 157 km^{-1}	0 to 79 km^{-1}	Increased
Trapping	< -157 km^{-1}	< 0 km^{-1}	Significantly Increased

Table 3.1 General electromagnetic (EM) refractive conditions. Vertical profiles of refractivity (d*N*/dz) and modified refractivity (d*M*/dz) and associated impact on theoretical surface / radar horizon (*Distance to Surface Horizon*).

SEAWASP	MORIAH
Combination of four- and two-wire RS-422 and two-wire RS-485.	Exclusive two-wire RS-485 half duplex.
Separate port and starboard MET instrument masts, each with different functions and noninterchangeable.	All MET instrument masts have the same architecture and can be interchanged.
Any significant failure [bad starboard processor, bad Global Positioning System (GPS) or compass] shuts down the whole system.	A significant or minor failure can be tolerated via reconfiguration of MET Instrument masts.
IR sensors in starboard MET mast.	IR sensors are located in a separate IR Instrument Mast (IM) reducing the amount of disturbance and lessening the chance of failure due to reliance on Met Instrument masts.

Table 4.1 Differences between SEAWASP and MORIAH hardware. From Reference (JHU/APL Hardware Technical Description for the METOC Sensor Equipment).

USS Anzio			USS Cape St. George		
Event	**Date (1998)**	**Longitude**	**Event**	**Date (1998)**	**Longitude**
Depart Norfolk	N/a	W076	Depart Norfolk	10 Jun	W076
Enter Med Sea	N/a	W006	Enter Med Sea	20 Jun	W006
Enter Suez Canal	8 Nov	E032	Enter Suez Canal	29 Aug	E032
Enter Arabian Gulf	13 Nov	E057	Enter Arabian Gulf	6 Sep	E057
Exit Arabian Gulf	20 Nov	E057	Exit Arabian Gulf	7 Sep	E057
Enter Suez Canal	26 Nov	E032	Enter Arabian Gulf	8 Sep	E057
Exit Med Sea	30 Nov	W006	Exit Arabian Gulf	28 Sep	E057
Return Norfolk	10 Dec	W076	Enter Arabian Gulf	2 Oct	E057
			Exit Arabian Gulf	19 Nov	E057
			Enter Suez Canal	26 Nov	E032
			Exit Med Sea	30 Nov	W006
			Return Norfolk	10 Dec	W076

Table 6.1 Anzio and Cape St. George logs: Event, Date, and Longitude Position.

Measured Parameter	**Sensor Used**	
	SEAWASP	**Planned MORIAH**
Air Temperature	Resistance Thermometer Device (RTD)	RTD
Sea Temperature (SST)	Thermistor (SWIT) / IR (mast)	Thermistor (SWIT) / IR (mast)
Air Humidity	Capacitance	Capacitance
Barometric Pressure	Diaphram	Diaphram
Vector wind	Propeller, vane	Sonic

Table 6.2 Measured Parameters and SEAWASP / Planned MORIAH Sensors.

Algorithm Categories	MORIAH METOC Measurements:	Pressure	Air Temp.	Relative Humidity	Relative Wind	Solar Radiation	IR Sky Temp.	IR Sea Surface Temp.	SeaWater Intake Temp.	SST - Floatsonde
	Met Pole Data									
	Conversion from Sensor Units	X	X	X	X	X	X	X	X	
	Compute Instantaneous Values									
	Select Met Pole	X	X	X	X	X	X	X	X	
	Compute Averages	X	X	X	X	X	X	X	X	
	Rocketsonde									
	Conversion from Sensor Units	X	X	X						
	Compute Instantaneous Values									
	Find Bad Data	X	X	X						
	Recalculate Adjusted Data	X	X	X						
	Filter Modified Refractivity Profile									
	Extrapolate Using Standard Atmosphere									
	Mast									
	Conversion from Sensor Units	X			X					
	Compute Instantaneous Values									
	Floatsonde									
	Conversion from Sensor Units		X	X						X
	Compute Instantaneous Values									
	Refractivity Profile Models									
	Check Input Data	X	X	X				X	X	
	Profile Calculation – LKB Model									
	Merge Surface / Rocketsonde Profiles									

Table 6.3 MORIAH METOC Measurement Capability and Algorithm Categories.

Possible and performed	Possible, but not performed due to evaluation/verification stage	Not possible, Capability Not Functional
• Apparent vector wind • Air Temperature • RH • SST • Barometric Pressure	• Vertical Atmosphere Profile (Rocketsonde) • Sea Surface float (Floatsonde)	• Insolation • Cloud Height • Visibility and IR extinction • Rain rate • Wave height, direction, and period

Table 6.4 MORIAH Measurement system and algorithm evaluation status.

Data File	Recording Frequency
Mast Average	5 min
Mast Instantaneous (Raw)	10 sec
Ship's Position Data	30 sec
Rocketsonde	variable *
Catamaran Average	TBD
CVT Model Evaporation Duct Profile	TBD
PLS Model Evaporation Duct Profile	TBD
SMM Model Evaporation Duct Profile	TBD
Ducting History	TBD

Table 6.5 SEAWASP data file types and Recording frequency.

* Rocketsonde deployment is requested by the SEAWASP system logic.

MORIAH ORD Performance Specification			SEAWASP Performance (DISTANCE < 10 KM)		
PARAMETER	THRESHOLD	OBJECTIVE	SENSOR	THRESHOLD	OBJECTIVE
Wind Direction	± 2.0° Azimuth	± 2.0° Azimuth	± 90.4 °	5.75%	5.75%
Wind Speed *	± 1.0kt	± 0.5kt	± 7.2 kt	33.88%	16.22%
Air Temperature	± 0.5° C	± 0.5° C	± 0.5 ° C	97.13%	97.13%
Relative Humidity	± 3.0%	± 1.0%	± 2.4 % C	96.30%	74.54%
Sea Temperature	± 0.5° C	± 0.3° C	± 0.6 ° C	97.33%	64.59%
Atmospheric Pressure	± 1.0mb/hPa	± 1.0mb/hPa	± 1.5 mb/hPa	29.42%	29.42%

Table 8.1 MORIAH ORD Requirements and SEAWASP Accuracy Performance. The source data set for this comparison is 5-minute averaged data covering the period from 25 August to 10 December with a total of 15395 records available. Application of 10 km distance criteria resulted in 1234 records.

MORIAH ORD Performance Specification. *THRESHOLD* and *OBJECTIVE* columns are the MORIAH ORD instrument / sensor performance requirements for the Evaporation Duct Parameters listed under the *PARAMETER* column. Threshold performance is the minimum acceptable performance level for the MORIAH sensors and system, and the higher Objective level is the optimal target for performance. Wind Direction is not a refractive variable, and the SEAWASP met mast wind is not MORIAH intended sensor for wind. A separate sensor will be mounted on the ship mast for this measurement. SEAWASP winds are included in this evaluation because it is the primary criteria for determining met mast selection / data validity. Wind direction performance indicates the consistency of applying met mast criteria for determining data validity.

SEAWASP Performance. Threshold and Objective performance is inferred through a comparison of Anzio and Cape St. George simultaneous SEAWASP measurements when the separation distance is less than 10 kilometers. Accuracy performance is the RMS difference between these measurements from the SEAWASP 5-minute averaged value which are listed in the *SENSOR* column. BLUE numbers meet the ORD requirements, and RED numbers fail. *THRESHOLD* and *OBJECTIVE* columns report the percentage of the 10 kilometer data set which meet the MORIAH ORD requirements.

* Range of SEAWASP *Wind Speed* values do not reach ORD Second Level requirements. Only First Level Requirements are used. Second Level requirements are Speed Range within 61 to 125 kt and Speed Accuracy for Threshold and Objective within ± 2.5 kt and ± 1.0kt.

METOC Parameter	Blanc		Dockery	SEAWASP
	Sensor	Ship Influence		
U <= 20 m/s	± 0.5 m/s	10%	10%	27.2%
U > 20 m/s	± 1.0 m/s	10%	10%	- - -
SST	± 0.5C	+0.3C	± 0.25C	± 0.55C
Tair (day)	± 0.3C	+0.5C	± 0.25C	± 0.47C
Tair (night)	± 0.3C	0.0 C	± 0.25C	± 0.47C
Relative Humidity	- - -	- - -	2%	0.5%

Table 8.2 METOC Measurement Accuracy Requirements for Evaporation Duct Height Determination. The data set for this comparison is 5-minute averaged data covering the period from 25 August to 10 December with a total of 15395 records available. Application of 5 km distance criteria resulted in 776 records.

Blanc and **Dockery.** Guidance/specifications for evaluating SEAWASP sensor accuracy performance. Blanc columns provide the guidelines for sensor limits of accuracy based on expected sensor performance in a ship contaminated environment. *Dockery* column is the sensor accuracy specifications necessary to analyze evaporation duct heights within the necessary 2 m. *SEAWASP* column lists the results of sensor performance.

Ship	SEAWASP Minimum / Maximum Measurements and Range of Values(Δ)			
	Air-Sea Temperature Difference ASTD (C)	Relative Humidity (%)	Wind Speed (knots)	Evaporation Duct Height (m)
Anzio	+1.25 to +1.92 (ΔT = 0.67)	53.23 to 57.58 (ΔRH = 4.35)	10.01 to 14.85 (ΔU = 4.84)	25.1 to 42.9 (Δz = 17.8)
Cape St. George	+1.87 to +2.57 (ΔT = 0.70)	54.26 to 61.00 (ΔRH= 6.74)	9.41 to 12.58 (ΔU = 3.17)	27.1 to 77.5 (Δz = 50.4)

Table 8.3 Refractive Parameter Range for Evaporation Duct Heights > 25 m. Data is from 5 km Distance Criteria, and the values are each ship's measurement range coincident with diverging evaporation duct (heights > 25 m).

Ship	Period (month / day)	MORIAH ORD		Records Tot / Rec / (A_o)
		Threshold	Objective	
Anzio	9/05 – 12/10	96.9 %	98.1%	27936 / 15581 (55.7 %)
Cape St. George	5/27 – 12/21			59976 / 58635 (97.8 %)

Table 8.4 System Performance Reliability for MORIAH ORD Specifications (A_o). For the specified time period (*Period*) and ship (*Ship*), *Records* provide the A_o, *Threshold* is the minimum acceptable A_o, *Objective* is the optimal target for A_o.

Records Column Tot / Rec / (A_o). *Tot* is the total possible number of mast average records in the specified *Period* which is calculated by the product of total hours in the period and number of records in 1 hour (12 records). *Rec* is the total number of mast average records present in the data set for the specified period. (A_o) is the system's Operational Availability which is the ratio of *Tot* and *Rec.*

Note: Power surge on Anzio resulted in approximately 40 day loss in system usable time which significantly decreased A_o.

Ship	Date 1998	Records Tot / Rec / QC (%)	Data Gaps (no data / invalid data)					
			> 15min ≤ 1 hr	≤ 2 hr	≤ 3 hr	≤ 4 hr	>5 hr ≤ 48 hr	> 72 hr
TOTAL PERIOD (Transit / Onstation / Transit)								
Anzio	9/05 – 12/10	27936 / 15581 / 7778 (28%)	6 / 1203	2 / 51	0 / 13	1 / 6	4 / 22	5 / 4
Cape St. George	5/27 – 12/21	59976 / 58635 / 29417 (49%)	6 / 2772	3 / 316	0 / 78	0 / 33	3 / 71	7 / 7
TRANSIT - 'SYSTEM ON' TO ONSTATION (Onstation Entrance Straits of Hormuz)								
Anzio	9/05 – 11/13	19872 / 7877 / 3770 (48%)	6 / 541	2 / 25	0 / 6	1 / 3	4 / 15	2 / 2
Cape St. George	5/27 – 9/06	29376 / 29226 / 15289 (52%)	5 / 1370	2 / 152	0 / 34	0 / 14	1 / 27	4 / 4
ONSTATION (SouthWest Asia Area of Operations)								
Anzio	11/13 – 11/20	2304 / 2281 / 857 (38%)	0 / 81	0 / 9	0 / 7	0 / 3	0 / 7	0 / 1
Cape St. George	9/06 – 11/19	21600 / 21107 / 9821 (47%)	1 / 860	0 / 130	0 / 36	0 / 16	1 / 27	2 / 4
TRANSIT - OFF-STATION TO 'SYSTEM OFF' (Off-station Entrance Straits of Hormuz)								
Anzio	11/20 – 12/11	6336 / 5990 / 3242 (54%)	0 / 528	0 / 16	0 / 3	0 / 2	0 / 8	1 / 3
Cape St. George	11/19 – 12/21	9504 / 8872 / 4616 (52%)	0 / 351	1 / 36	0 / 10	0 / 4	1 / 15	1 / 2

Table 8.5 System Performance Reliability for AEGIS.

Records Tot / Rec / QC. *Tot* is the total possible number of mast average records in the specified *Period* which is calculated by the product of total hours in the period and number of records in 1 hour (12 records). *Rec* is the total number of mast average records present in the data set for the specified period. *QC* is the total number of *Rec* records which remain after system validates data.

Records (%). The (%) represents the Operational Data Reliability and is the ratio of *QC* to *Rec*.

Data Gaps. are separated in *no data* and *QC*. *No data* refers to data gaps that have missing records. *QC* refers to records which are flagged with –99 values. Data which does not meet validation criteria is not used (data gap) and flagged with –99.

Ship	Dates	Records Tot / Rec / QC (% / %)	Data Gaps (no data / QC)					
			>15 min ≤ 1 hr	≤ 2 hr	≤ 3 hr	≤ 4 hr	> 5 hr ≤ 48 hr	> 72 hr
NOVEMBER 1 – 30								
Anzio	November	8640/8508/3312 (98.5% / 38.9 %)	2 / 531	0 / 37	0 / 14	1 / 4	0 / 21	0 / 4
Cape St. George	November	8640/8557/3992 (99.0% / 46.7 %)	1 / 439	0 / 42	0 / 9	0 / 3	0 / 9	0 / 2

Table 8.6 System Performance Reliability for November is identical to the previous table 8.5. This table provides A_o and Operational Data Reliability statistics for November. November contains a mixture of transit and patrol ship profiles. For the *Records (%)* column, the first % is the A_o statistics (Rec / Tot) and the second % is the Operational Data Reliability (QC / Rec).

Zulu Day	Anzio			Cape St. George		
	A	B	C	A	B	C
1101	5150 / 3372 4167 / 4355	0 3321	0 49% - 88%	2493 / 6107 4427 / 4173	579 1413	29% - 36% 52% - 68%
1102	3030 / 5513 2009 / 6534	295 763	36% - 39% 24% - 32%	1584 / 6914 4833 / 3665	319 1100	19% - 22% 57% - 70%
1103	7 / 8539 816 / 7730	2117 2179	<1% - 22% 10% - 33%	1753 / 6841 4822 / 3772	271 1566	20% - 24% 56% - 74%
1104	1040 / 7506 1639 / 6907	32 4628	< 1% 19% - 73%	3229 / 5368 4924 / 3673	640 1079	38% - 45% 57% - 70%
1105	4752 / 3787 4399 / 4140	0 3996	0 52% - 98%	4836 / 3756 1947 / 6645	590 350	56% - 63% 23% - 27%
1106	3095 / 4095 4418 / 2772	22 2522	< 1% 61% - 97%	618 / 8002 2316 / 6304	111 2103	1% 27% - 53%
1107	2570 / 5974 3252 / 5292	234 2781	30% - 33% 38% - 71%	431 / 8182 293 / 8320	103 1854	1% 3% - 25%
1108	1984 / 6559 3607 / 4936	357 2306	23% - 27% 42% - 69%	212 / 8365 1715 / 6862	183 17	3% - 5% < 1%
1109	4360 / 4183 3491 / 5052	191 2678	51% - 53% 41% - 72%	172 / 8446 1942 / 6676	412 1546	2% - 7% 23% - 41%
1110	5234 / 3310 2967 / 5577	627 1846	61% - 69% 35% - 56%	139 / 8471 3686 / 4924	2078 285	2% - 26% 43% - 46%
1111	5280 / 3266 3779 / 4767	632 1406	62% - 69% 44% - 61%	3720 / 4883 3523 / 5080	285 914	43% - 47% 41% - 52%
1112	5440 / 2818 3944 / 4314	657 1078	66% - 74% 48% - 61%	2563 / 6033 3862 / 4734	416 2031	30% - 35% 45% - 69%
1113	5144 / 3394 3700 / 4838	1003 1040	61% - 72% 43% - 56%	3381 / 5183 5258 / 3306	391 931	40% - 44% 61% - 72%
1114	3737 / 4799 3601 / 4935	537 835	44% - 50% 42% - 52%	2880 / 5681 5128 / 3433	1071 465	34% - 46% 60% - 65%
1115	503 / 8035 3847 / 4691	1685 928	6% - 26% 45% - 56%	2354 / 6228 4242 / 4340	478 1316	27% - 33% 49% - 65%
1116	3390 / 5147 4424 / 4113	255 1509	40% - 43% 52% - 70%	5037 / 3519 2213 / 6343	299 779	59% - 62% 26% - 35%
1117	2237 / 6287 4335 / 4169	423 828	26% - 31% 51% - 61%	3156 / 5402 4535 / 4023	338 1994	37% - 41% 53% - 76%
1118	2187 / 6354 4729 / 3812	366 1363	26% - 30% 55% - 71%	4076 / 4480 3853 / 4704	174 1535	48% - 50% 45% - 63%
1119	2810 / 5731 4792 / 3749	280 2085	33% - 36% 56% - 81%	2712 / 5849 4205 / 4356	19 1475	< 1% 49% - 66%
1120	4815 / 3727 4226 / 4316	380 1843	56% - 61% 50% - 71%	2682 / 5919 5051 / 3550	180 1236	31% - 33% 59% - 73%
1121	3735 / 4808 4935 / 3608	78 2689	< 1% 58% - 89%	2722 / 5887 5057 / 3552	71 1946	< 1% 59% - 81%
1122	3942 / 4586 4569 / 3959	135 2835	46% - 48% 53% - 87%	2934 / 5670 4819 / 3785	58 1787	< 1% 56% - 77%
1123	2930 / 5608 5349 / 3189	173 1564	34% - 36% 63% - 81%	1405 / 7200 4719 / 3886	228 1157	16% - 19% 55% - 68%
1124	4383 / 4160 3140 / 5403	75 3407	1% 37% - 77%	3089 / 5530 3557 / 5062	71 4796	1% 41% - 97%
1125	3816 / 4728 3642 / 4902	176 3018	45% - 47% 43% - 78%	2689 / 5908 4768 / 3829	2 3332	< 1% 56% - 94%
1126	3377 / 5160 6131 / 2406	67 1722	< 1% 72% - 92%	2837 / 5768 6233 / 2372	152 1102	33% - 35% 72% - 85%
1127	5099 / 3430 5042 / 3487	159 3103	60% - 62% 59% - 96%	4031 / 4586 5576 / 3041	382 1788	47% - 51% 65% - 86%
1128	4957 / 3584 5130 / 3411	264 2056	58% - 61% 60% - 84%	4186 / 4425 6105 / 2506	998 1202	58% - 61% 60% - 84%
1129	5109 / 3431 5613 / 2927	69 2117	1% 66% - 91%	3797 / 4812 6400 / 2209	642 215	44% - 52% 74% - 77%
1130	2259 / 6276 7727 / 808	30 488	< 1% 91% - 96%	2920 / 5666 7840 / 746	270 419	34% - 37% 91% - 96%

Table 8.7 November Data Counts Using Instantaneous Data. Table lists port and starboard met mast data counts for wind (U) and relative humidity / air temperature (RHT) criteria. Percentages of valid data for wind (U) criteria and relative humidity / air temperature (RHT) are also listed.

A column: First number of each row is the number of records which are valid for wind (U) criteria (Port U Valid), and the second number is the number of records which are invalid for wind criteria (Port U Invalid). The top row is for the port met mast sensor, and the bottom number is for the starboard met mast sensor.

Port U Valid / Port U Invalid **Stbd U Valid / Stbd U Invalid**

B column: Top number is number of port met mast records which did not satisfy wind (U) criteria but satisfy the Relative Humidity / Temperature (RHT) criteria. Bottom number is number of starboard met mast records which did not satisfy wind (U) criteria but satisfy the Relative Humidity / Temperature (RHT) criteria.

Port U Invalid RHT Valid **Stbd U Invalid RHT Valid**

C column: Top numbers are for the port met mast, and the bottom numbers are for the starboard met mast. In each row, the first number is the valid wind (U) records versus total number of records for the day, and the second number is the sum of valid wind (U) records and relative humidity / temperature (RHT) valid records versus total number of records for the day. When the difference between the first and second number is 1% or less, only one number listed for that met mast.

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APPENDIX B. FIGURES

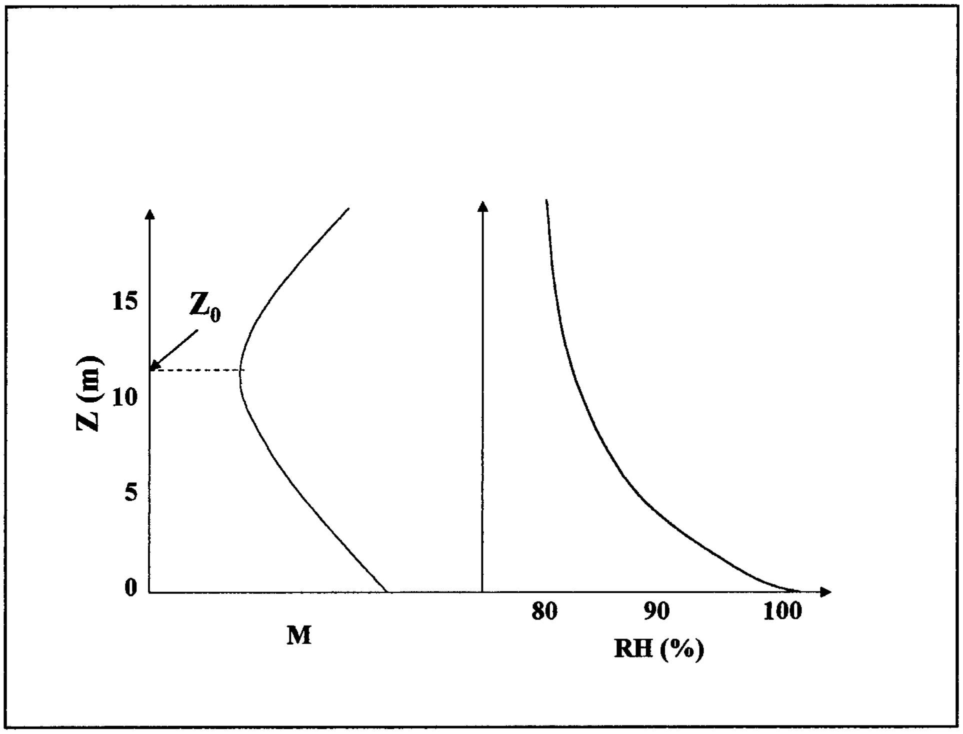


Figure 3.1 *M*-profile leading to a typical evaporation duct situation. The blue line represents the natural decrease in relative humidity (RH) from the water's surface to some height above the surface. The red line is the resulting modified refractivity (d*M*/dz) profile. Z_o is the evaporation duct height which is located at the refractivity minimum (d*M*/dz = 0) above a negative vertical refractivity profile (d*M*/dz < 0). In this example, Z_o is approximately 11 m above the water's surface.

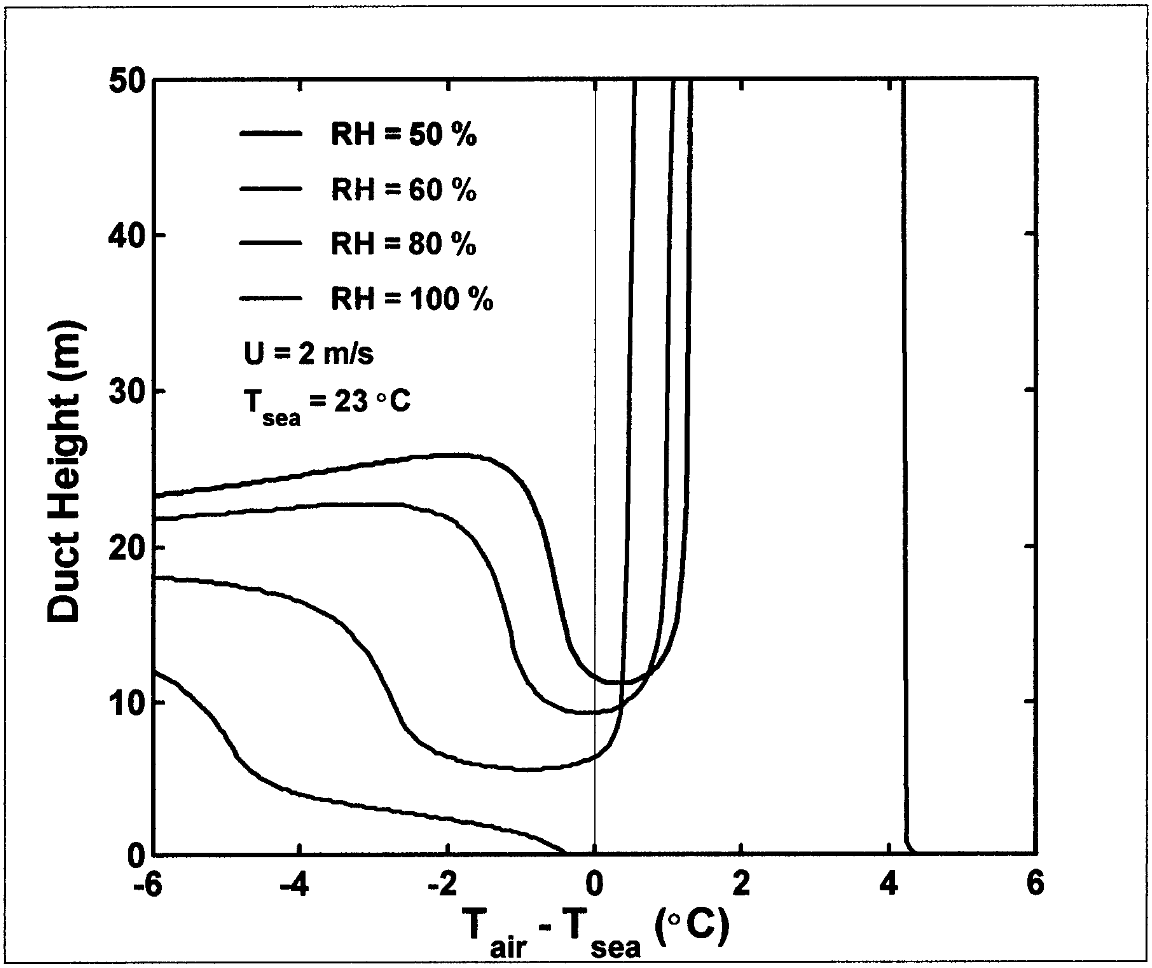


Figure 3.2 Bulk model evaporation duct heights for the light wind case (U = 2 m/s). Evaporation duct height solutions (colored lines) are for a fixed SST (Tsea = 23°C) and wind speed (2 m/s) values. The colored lines represent the duct height determinations for a particular relative humidity (RH) and air-sea temperature difference (Tair – Tsea ≡ ASTD). ASTD defines the surface-layer stability conditions where negative ASTD is unstable and positive ASTD is stable.

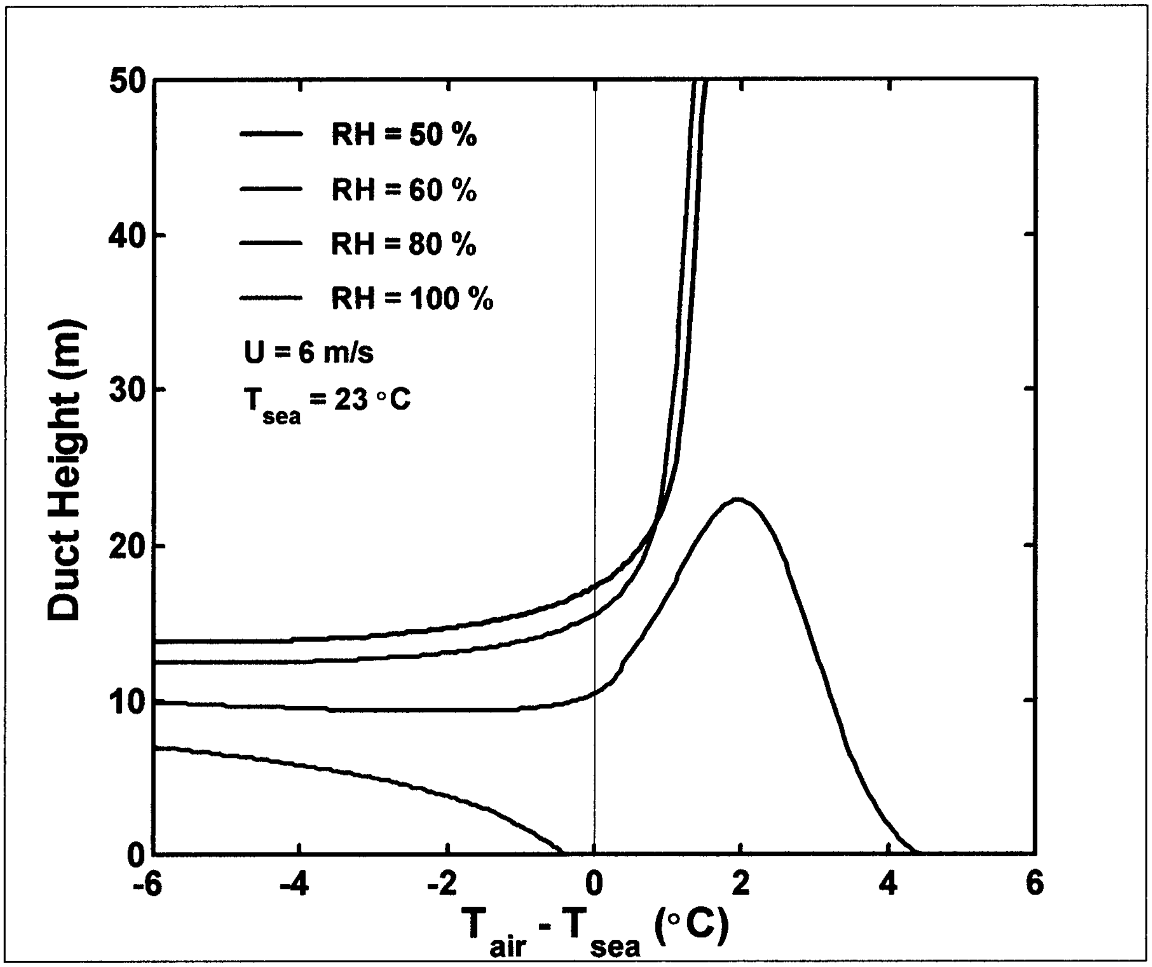


Figure 3.3 Bulk model evaporation duct heights for the moderate wind case (U = 6 m/s). Evaporation duct height solutions (colored lines) are for a fixed SST (Tsea = 23°C) and wind speed (6 m/s) values. The colored lines represent the duct height determinations for a particular relative humidity (RH) and air-sea temperature difference (Tair – Tsea ≡ ASTD). ASTD defines the surface-layer stability conditions where negative ASTD is unstable and positive ASTD is stable.

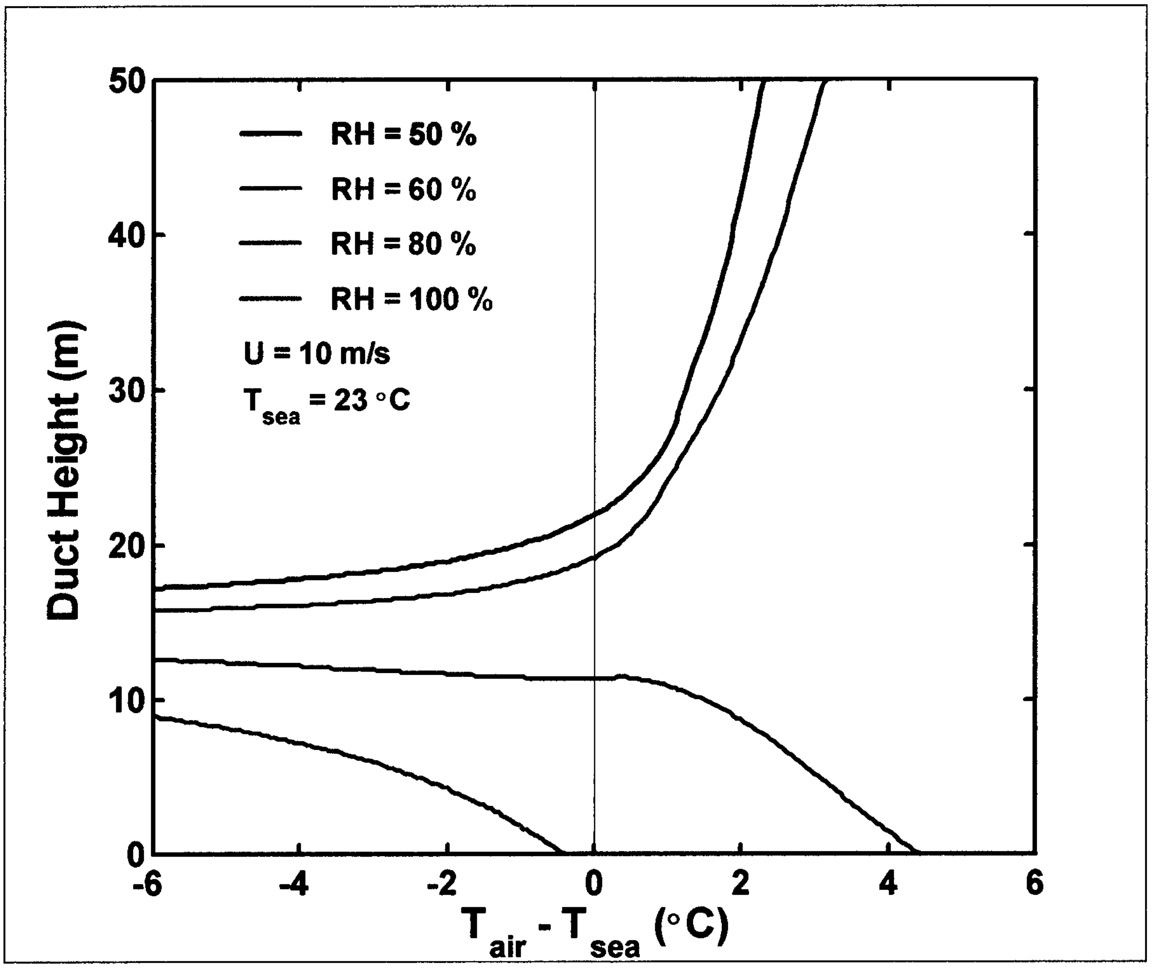


Figure 3.4 Bulk model evaporation duct heights for the strong wind case (U = 10 m/s). Evaporation duct height solutions (colored lines) are for a fixed SST (Tsea = 23°C) and wind speed (10 m/s) values. The colored lines represent the duct height determinations for a particular relative humidity (RH) and air-sea temperature difference (Tair – Tsea ≡ ASTD). ASTD defines the surface-layer stability conditions where negative ASTD is unstable and positive ASTD is stable.

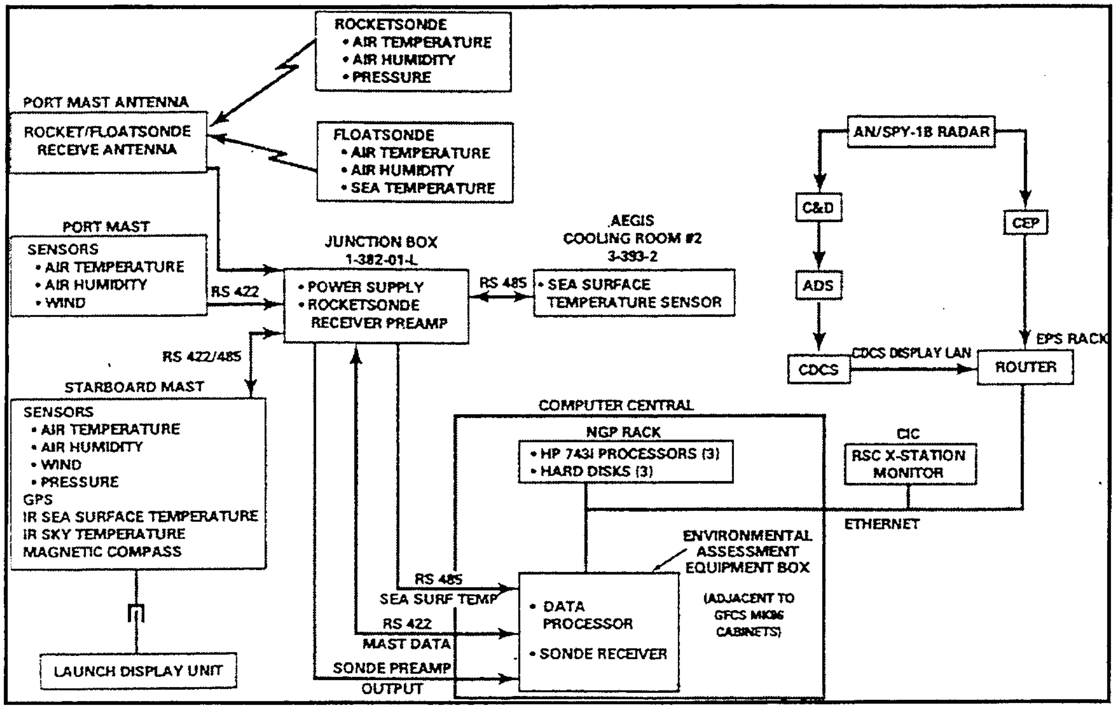


Figure 4.1 Overview of SEAWASP Environmental Characterization (EC) System Layout.

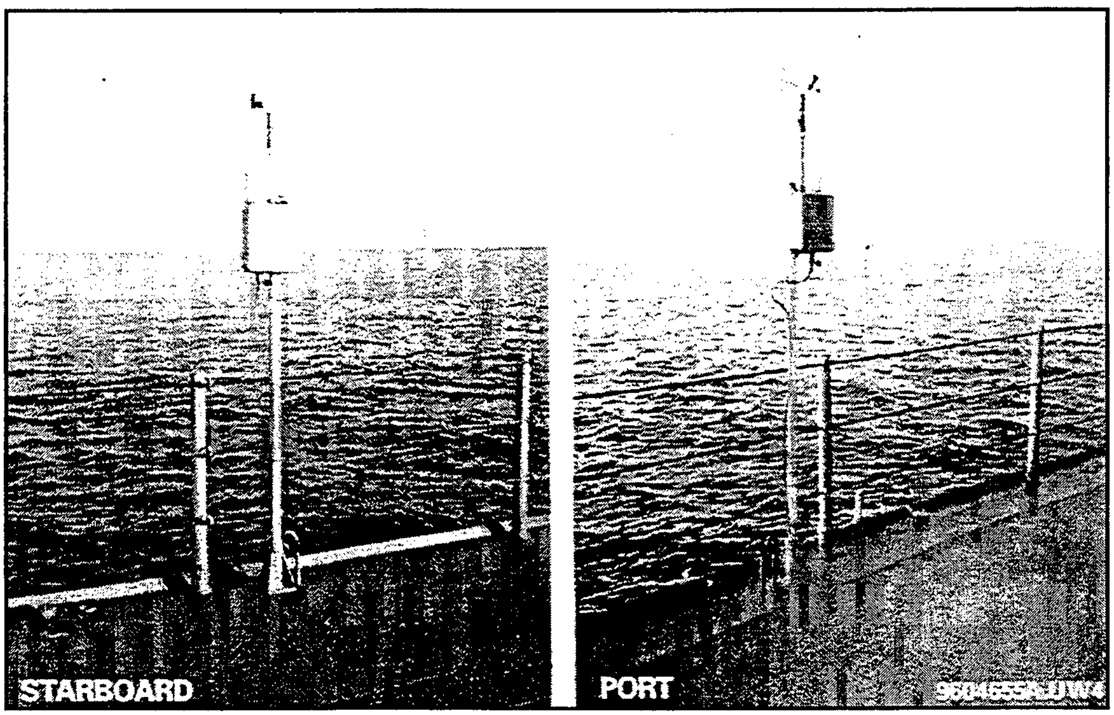


Figure 4.2 Starboard and Port SEAWASP Met Mast.

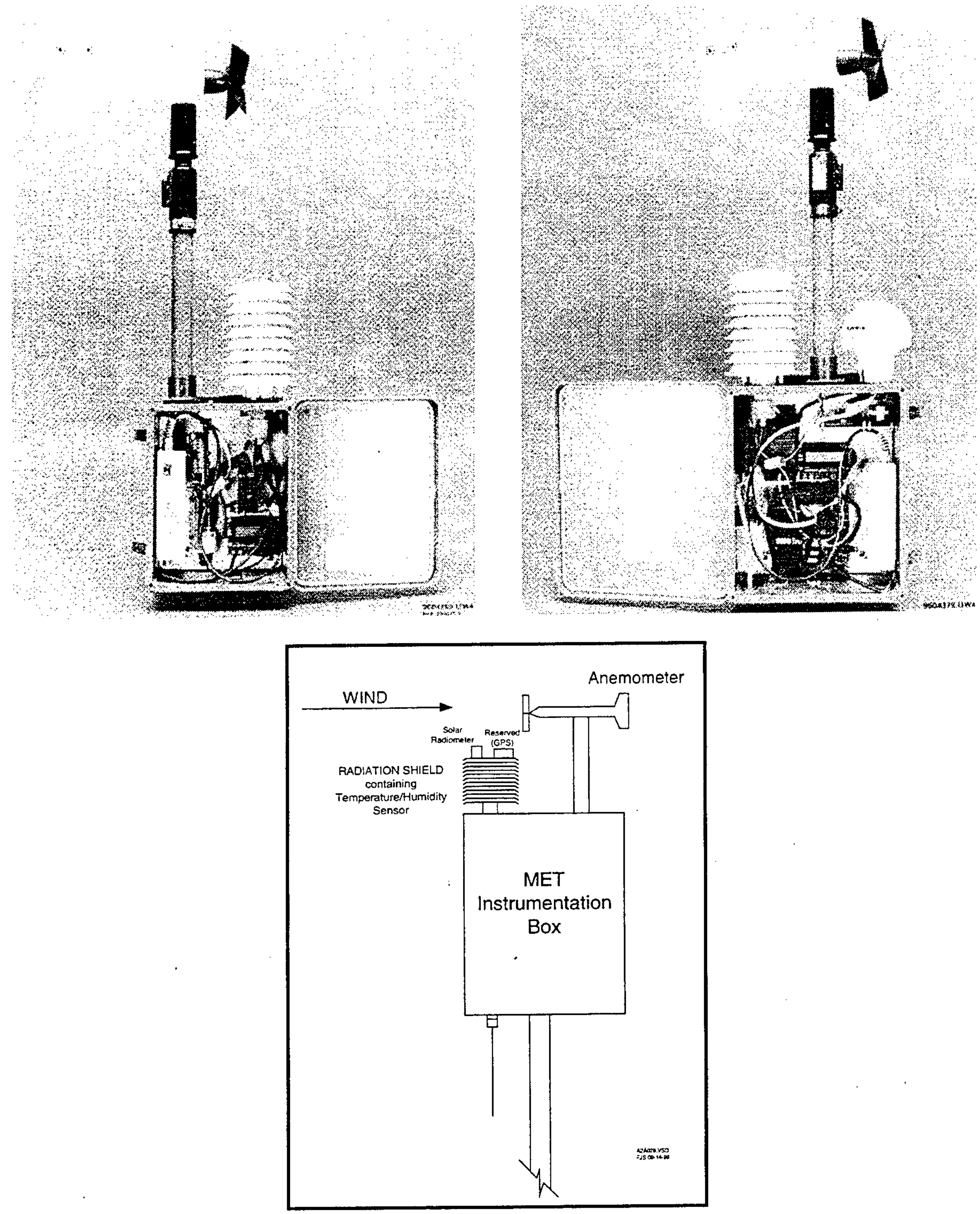


Figure 4.3 Port and Starboard Met Instrumentation Box. Photos (top) are the Met instrumentation boxes (Port on the Left and Starboard on the Right) that were deployed on the Anzio and Cape St. George. Both port and starboard boxes have measurement sensors for air temperature, relative humidity and relative wind. The starboard box also contains instrumentation for pressure, IR SST / cloud temperatures, and GPS. The current version of MORIAH (not depicted) has slight differences in the instrument configuration. MORIAH has a separate mast for IR Sensors, and port / starboard Met instrumentation suites are identical.

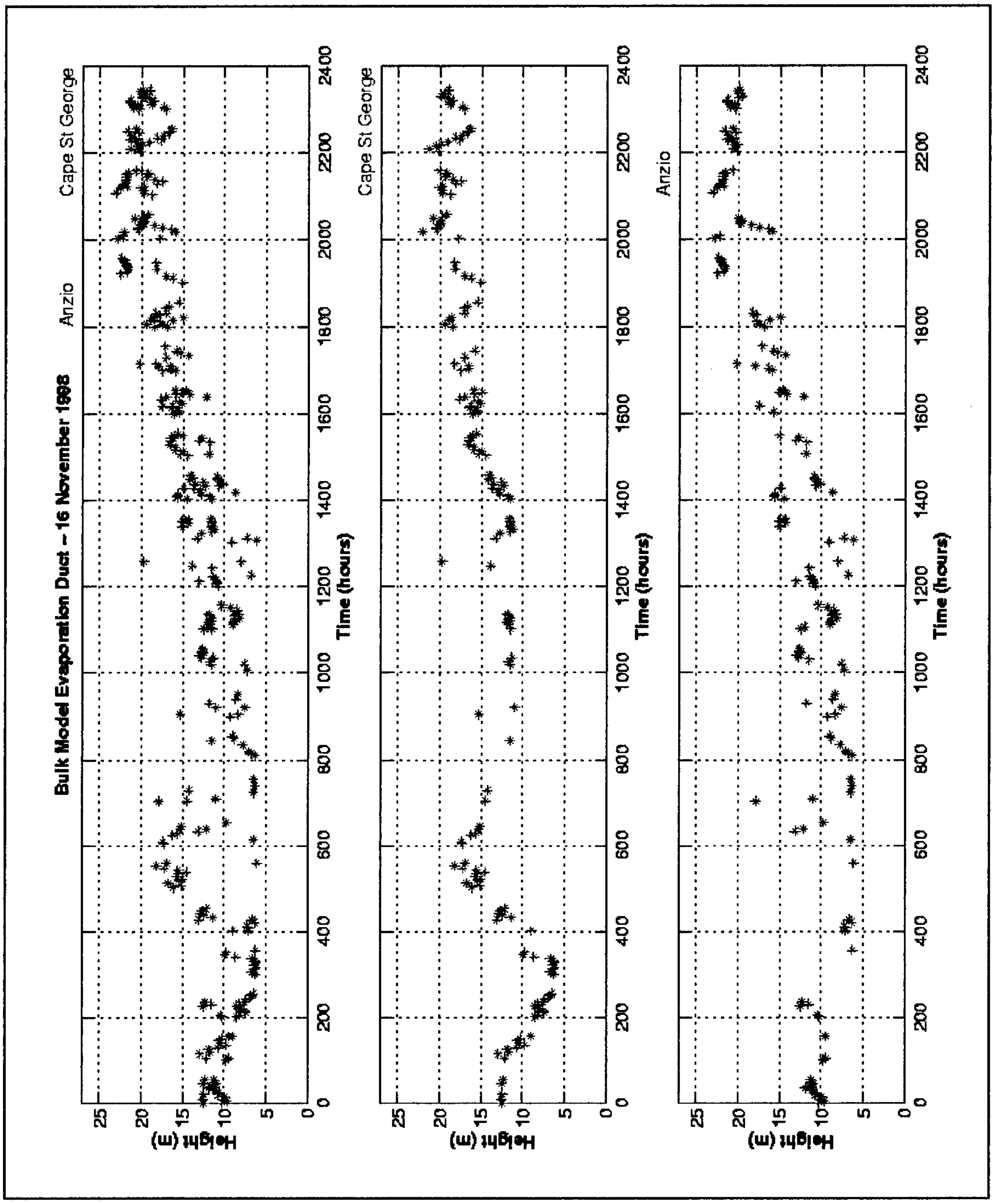


Figure 5.1 Bulk Model Evaporation Duct height for Anzio (red) and Cape St. George (blue). Evaporation duct height calculations are from the NPS adapted Bulk Evaporation Duct model. Top plot is the combined Anzio and Cape St. George time-series duct height solutions for the Zulu day of 16 November. The 2 plots below are the individual time-series.

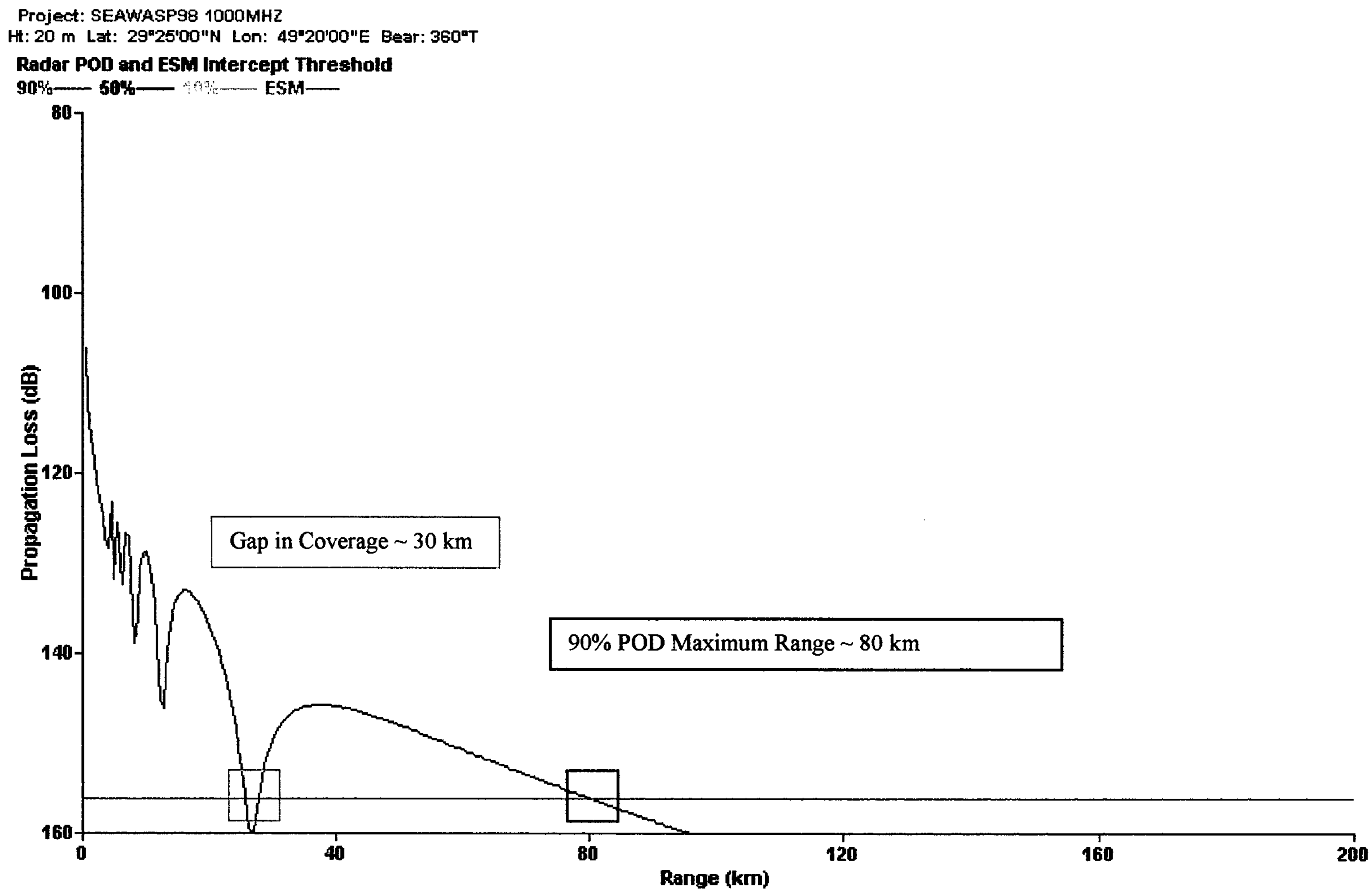


Figure 5.2 AREPS Propagation Loss profile for Cape St. George (04Z). Plot shows propagation loss over a horizontal distance . Red line is the threshold for 90% radar Pd. Detection occurs if propagation loss curve is above the threshold. The threshold line is for a 1000MHZ radar at 20 meter height to detect a small radar cross section target 90% of the time.

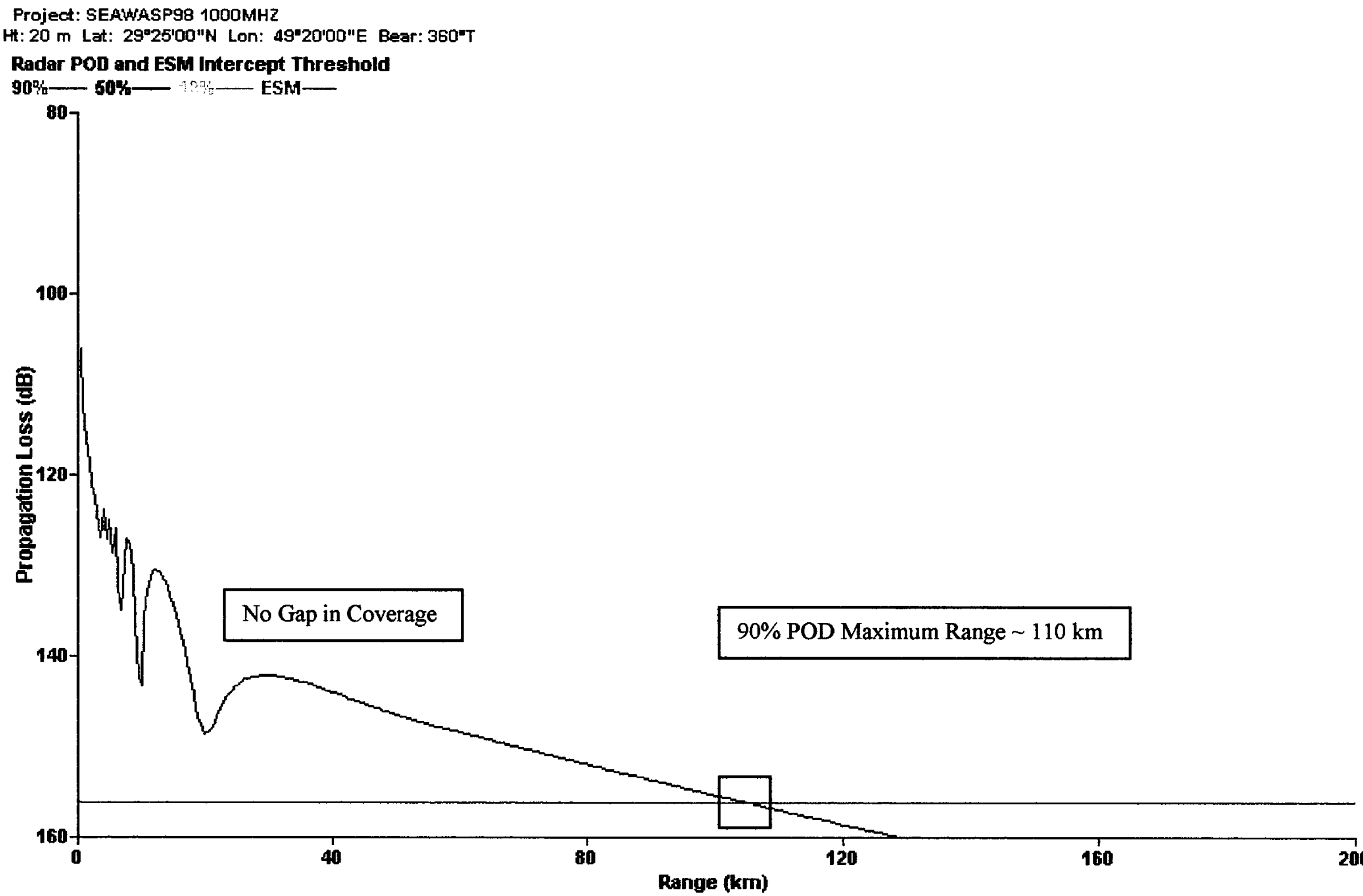


Figure 5.3 AREPS Propagation Loss profile for Cape St. George (06Z). Plot shows propagation loss over a horizontal distance. Red line is the threshold for 90% radar Pd. Detection occurs if propagation loss curve is above the threshold. The threshold line is for a 1000MHZ radar at 20 meter height to detect a small radar cross section target 90% of the time.

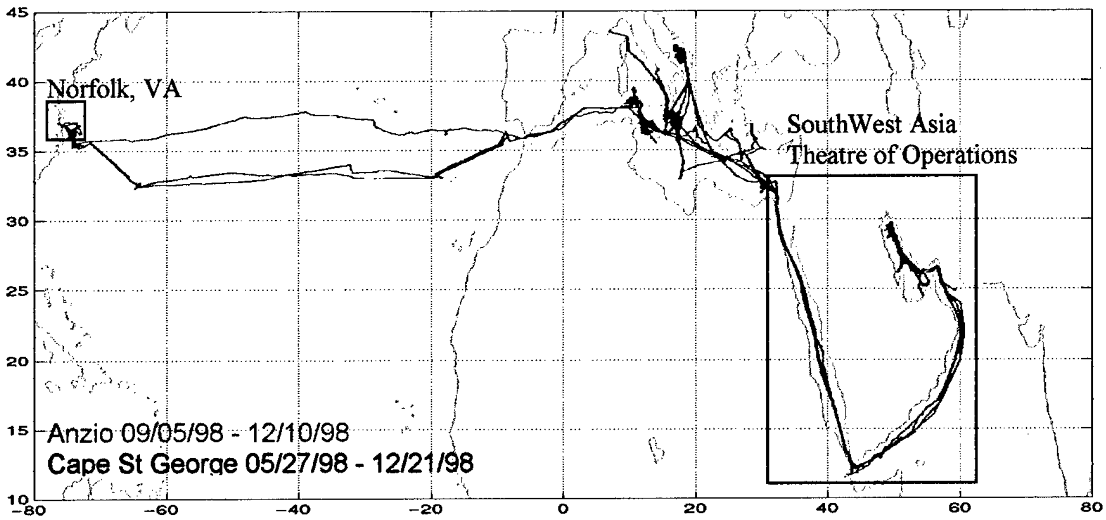


Figure 6.1 Anzio and Cape St. George ship tracks for the SEAWASP deployment covering the period of May – December 1998.

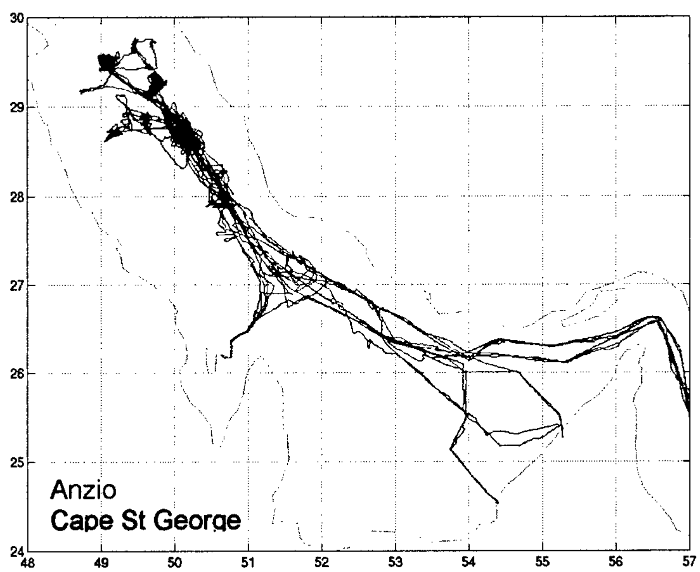


Figure 6.2 Anzio and Cape St. George ship tracks for the Arabian Gulf.

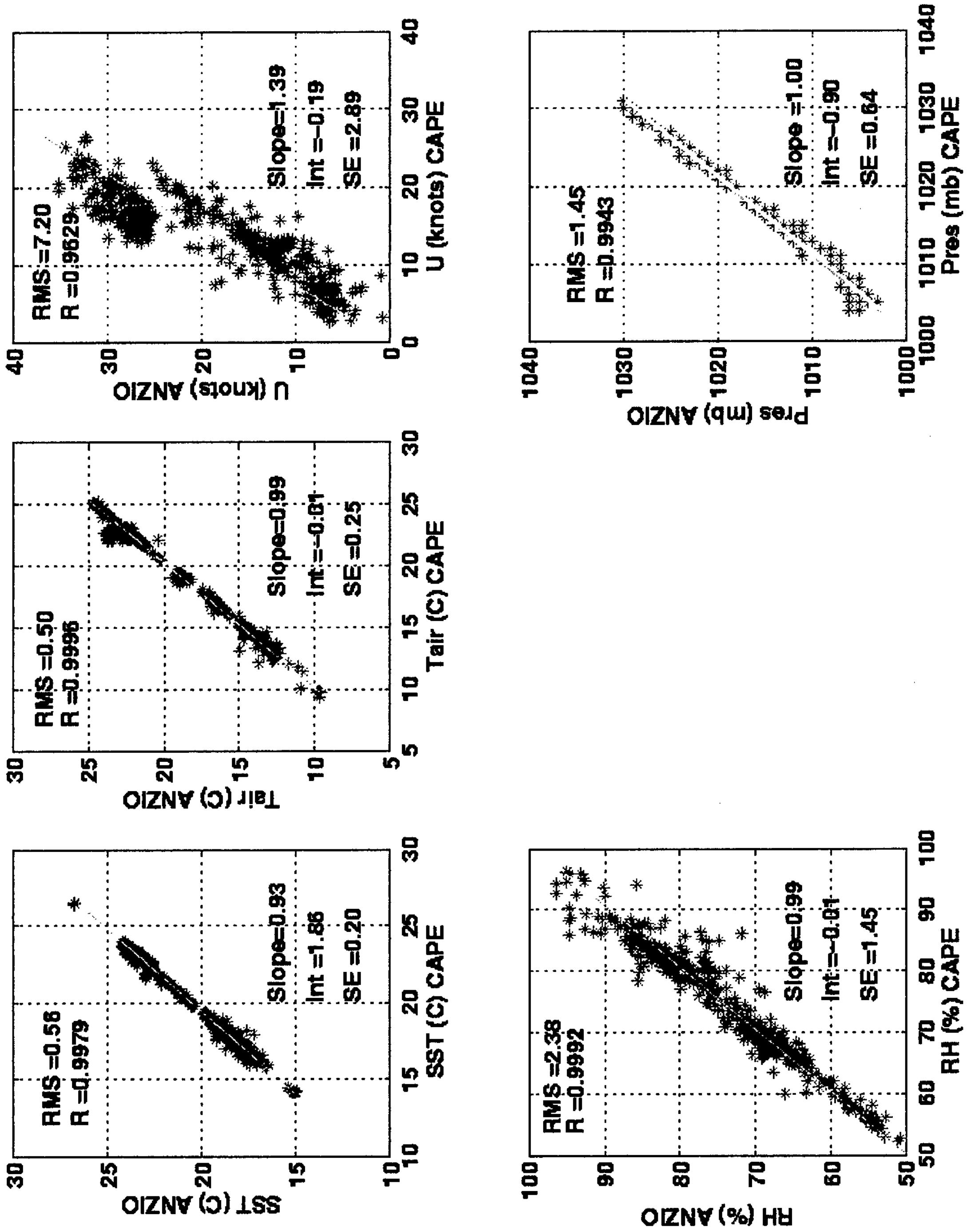


Figure 8.1 Scatterplots for Sensor Accuracy Analysis for MORIAH ORD Specifications. Comparative Analysis is based on distance criteria of 10 km resulting in sample size of 1234 points. Y-axis corresponds to Anzio SEAWASP measurements, and X-axis are Cape St. George SEAWASP measurements. Scatterplot statistics are labeled in the upper-left corner (RMS and R), and least-square fit statistics are listed in the lower right corner (Slope, Int, and SE).

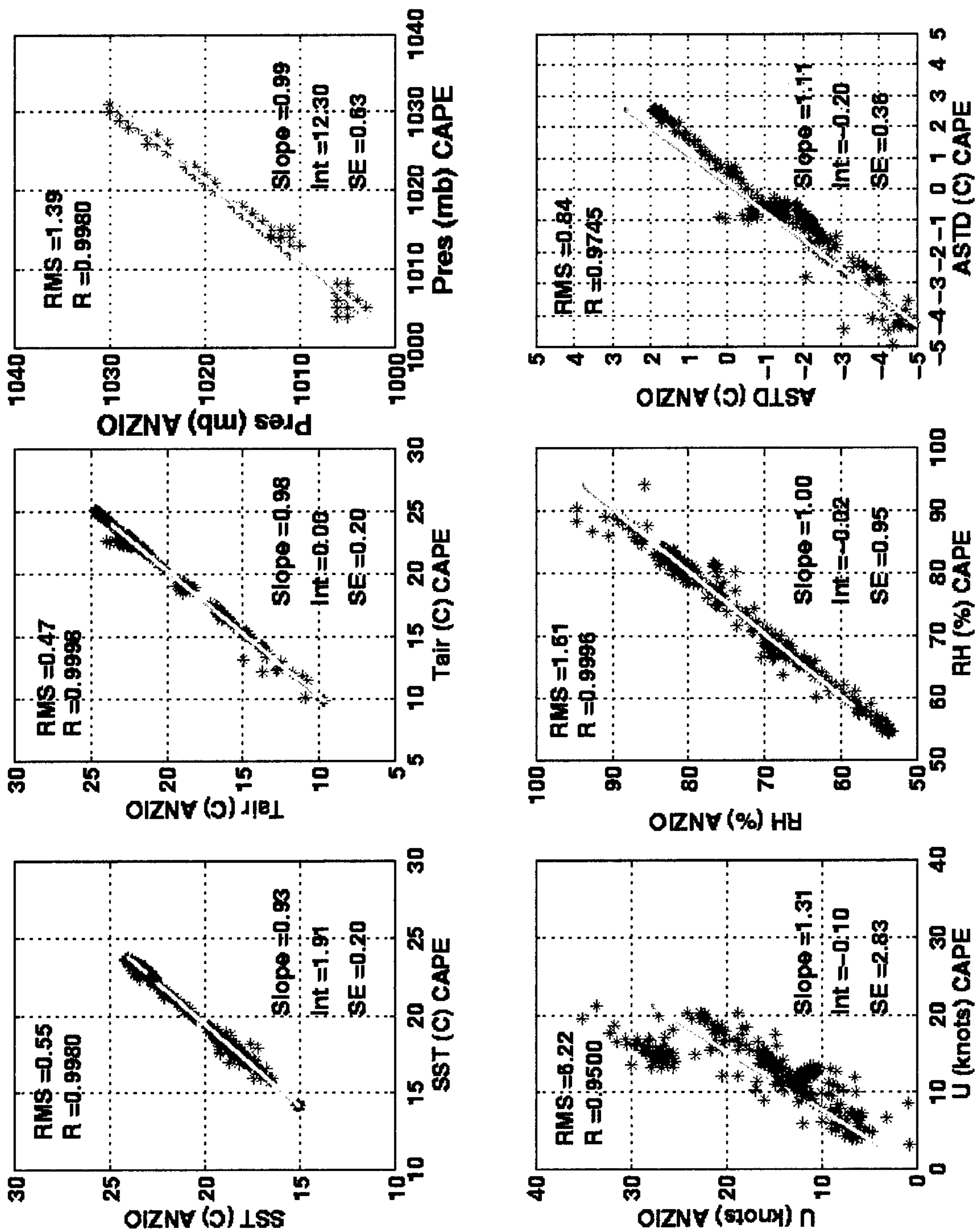


Figure 8.2 Scatterplots for Sensor Accuracy Analysis for AEGIS Specifications. Comparative Analysis is based on distance criteria of 5 km resulting in sample size of 776 points. Y-axis corresponds to Anzio SEAWASP measurements, and X-axis are Cape St. George SEAWASP measurements. Scatterplot statistics are labeled in the upper-left corner (RMS and R), and least-square fit statistics are listed in the lower right corner (Slope, Int, and SE).

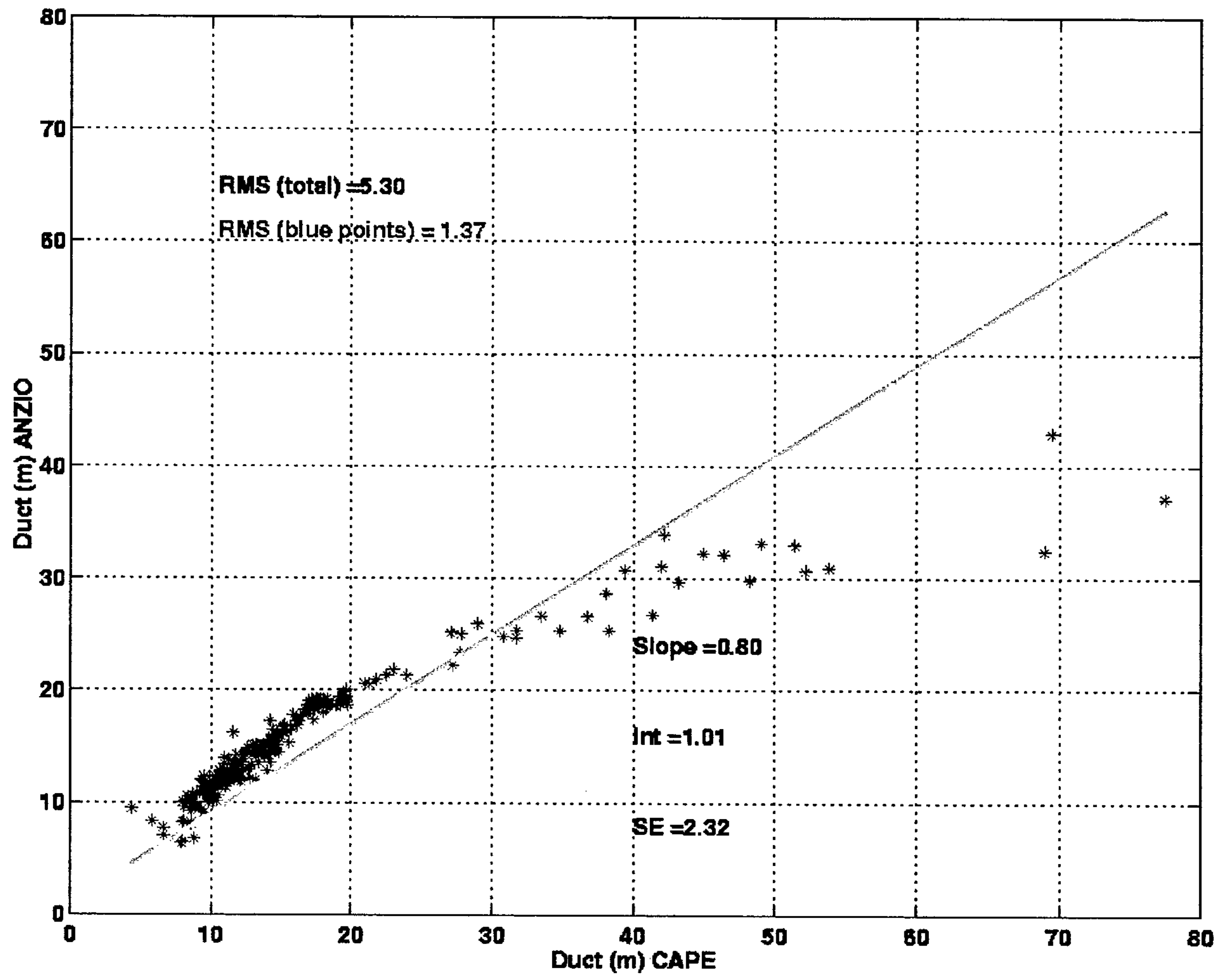
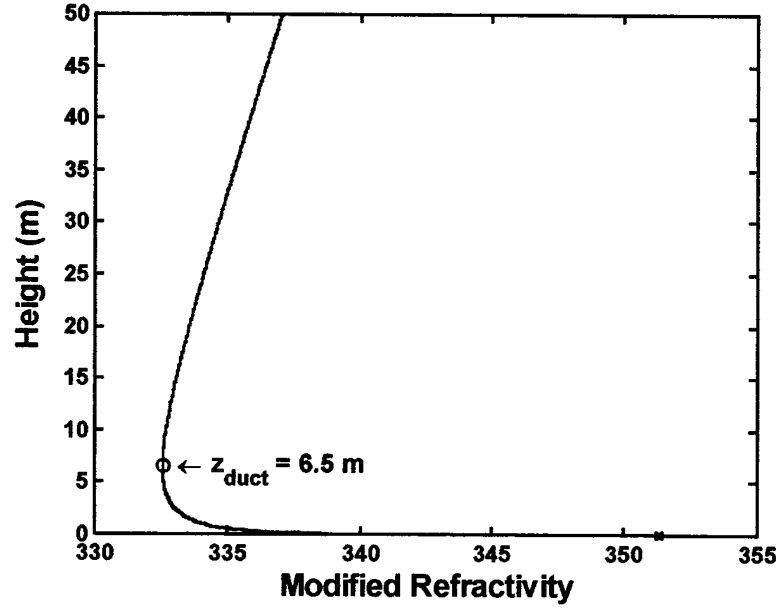


Figure 8.3 Bulk Evaporation Duct Model Heights.



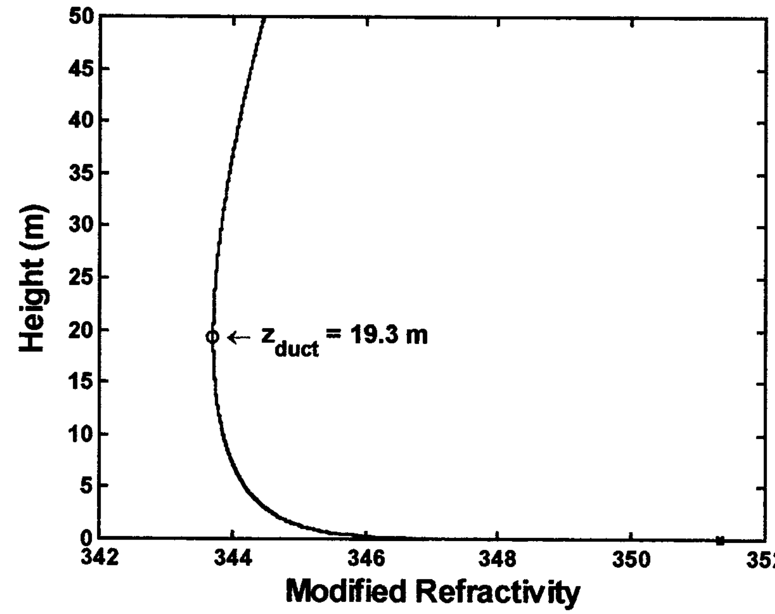


Figure 8.4 Modified Refractivity Profiles (dM/dz) for Different Stability Conditions. The plot on the left is for unstable conditions (ASTD < 0), and the plot on the right is for stable conditions (ASTD > 0). Zduct is the evaporation duct height which is found at the height where dM/dz = 0. In unstable conditions (left), the dM/dz profile leads to distinct Zduct height. In stable conditions (right), the dM/dz profile is not as distinct and Zduct is much harder to resolve. There is a wider range of heights where dM/dz ≈ 0.

APPENDIX C: MAST AVERAGE DATA FORMAT

Platform (USS Anzio / USS Cape St. George)

Average Ship's Course (degrees)

Average Ship's Speed (knots)

Current Ship's Latitude (degrees)

Current Ship's Longitude (degrees)

Sampling Rate (seconds)

Average Interval (seconds)

Total Samples used in Average

Source of Average Data and Selection Criteria (0,1,2,3) *

Uncorrected Average Wind Speed (knots)

Uncorrected Average Wind Direction (knots)

Average Air Temperature (degrees C)

Average Relative Humidity (%)

Average Atmospheric Pressure (millibars)

Average Infra Red Water Temperature (degrees C)

Average True Wind Speed (knots)

Average True Wind Direction (degrees)

Uncorrected Average Magnetic Compass (degrees)

Current Magnetic Declination (degrees)

Average Configuration File

GPS Validation Ratio

Date and Time

Corrected Average Magnetic Compass (degrees)

Average Hull Water Temperature (degrees C)

Average Infra Red Sky Temperature (degrees C)

Note: Average files are created with each 5-minute averaging event. Each event is saved in the respective Zulu day directory (MMDDYY) with a unique name in the following format hhmmss.MST.

MM	Month	DD	Day	YY	Year
hh	hour	mm	minute	ss	second

* Source of Average Data and Selection Criteria (0,1,2,3)

0 Average data selected from Starboard side using Wind Direction criteria.

1 Average data selected from Port side using Wind Direction criteria.

2 Average data selected from Starboard side using Highest Relative Humidity and Lowest Temperature criteria.

3 Average data selected from Port side using Highest Relative Humidity and Lowest Temperature criteria.

APPENDIX D: MAST INSTANTANEOUS SENSOR DATA FORMAT

Zulu Time of Day Hours (hh)*

Zulu Time of Day Minutes (mm)

Zulu Time of Day Seconds (ss)

Port Air Temperature (degrees C)

Port Air Relative Humidity (%)

Port Box Relative Humidity (%)

Uncorrected Port Wind Speed (knots)

Uncorrected Port Wind Direction (degrees)

Starboard Air Temperature (degrees C)

Starboard Air Relative Humidity (%)

Starboard Box Relative Humidity (%)

Uncorrected Starboard Wind Speed (knots)

Uncorrected Starboard Wind Direction (degrees)

Starboard Atmospheric Pressure (millibars)

Starboard Infra Red Water Temperature (degrees C)

Starboard Infra Red Sky Temperature (degrees C)

Hull Water Temperature (degrees C)

Starboard GPS Latitude (degrees)

Starboard GPS Longitude (degrees)

Starboard Compass Heading without Declination (degrees)

* Instantaneous files are separate files for each Zulu day. Each file has a unique name in the following format MMDDYY.INS.

MM Month DD Day YY Year

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APPENDIX E: SHIP'S POSITION DATA FORMAT

Zulu Date (MM/DD/YY)

Time of Day (GMT) (hhmmss)

Latitude (degrees)

Longitude (degrees)

Course (degrees)

Speed (knots)

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APPENDIX F: ROCKETSONDE DATA FORMAT

Sounding Type (RKT)

Launch Date (MM/DD/YY)

Launch Time (hh:mm:ss)

Data Quality (0,1,2) *

Latitude (degrees)

Longitude (degrees)

Record Time (hh:mm:ss.ff)

Atmospheric Pressure (millibars)

Atmospheric Temperature (degrees C)

Dew Point (degrees C)

Relative Humidity (%)

Modified Refractivity (*M*)

Altitude (meters)

Elapsed Time (seconds)

Virtual Temperature (degrees C)

* Data Quality

0	Bad Data Quality
1	Low Confidence
2	High Confidence

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LIST OF ACRONYMS

A_o	Operational Availability
APM	Advanced Propagation Model
AREPS	Advanced Refractive Effects Prediction System
ASTD	Air-Sea Temperature Difference
CG	Guided Missile Cruiser
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
CONUS	Continental United States
DIW	Dead-In-Water
EC	Environmental Characterization
EM	Electromagnetic
ESM	Electronic Surveillance Measure
GPS	Global Positioning System
HMI	Human-Machine Interface
IR	Infra red
JHU/APL	Johns Hopkins University Applied Physics Laboratory
LKB	Liu, Katsaros, Businger
met mast	Meteorological Mast
METOC	Meteorology and Oceanography
NAVAIR	Naval Air Systems Command
NDWMIS	New Digital Wind Measuring and Indicating System
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
ORD	Operational Requirements Draft
PE	Parabolic Equation

RMS	Root Mean Square
RPA	Radar Propagation Assessment
SEAWASP	Shipboard Environmental Assessment / Weapon System Performance
SECNAV	Secretary of the Navy
SMOOS(R)	Shipboard Meteorological and Oceanographic Observing System Replacement
SSC	Space and Naval Warfare Systems Center
SST	Sea Surface Temperature
SWIT	Sea-Water Inlet Temperature
VLS	Vertical Launch System
TEMPER	Tropospheric Electromagnetic Parabolic Equation Routine

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